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THESIS

SEA SPIKE MODELING

by

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Sea Spike Modeling

by

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Lieutenant, Taiwan Navy
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ABSTRACT

In this thesis a clutter voltage model for scattering from the sea surface is developed. A model for the scattering from a whitecap and a wave breaking occurrence model are combined to simulate the back scattered signal from one radar resolution cell. The simulation performed obtained the probability density function of sea clutter under different assumptions of wind velocities and wave breaking conditions. This model incorporates some measured quantities such as the mean clutter voltage and the correlation time as parameters. The probability density function depends on the parameters of this model. The obtained probability density functions do not confirm to any familiar simple density function.

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Thanks to all professors who taught me propagation and probability.

I. INTRODUCTION

In a radar system, the returned signal from a target is contaminated with clutter. The de ·'sion of a target presence is made based on the statistical description of targets. The clutter voltage in the envelope detector output is considered in this thesis and is treated as a random variable. Note that only the magnitude information but not phase is preserved by envelope detection. Therefore, in this thesis, "clutter voltage" will always mean the magnitude only.

The receiver output power is proportional to clutter cross section. The clutter voltage is proportional to the square root of clutter cross section.

In a radar receiver, components unavoidably generate thermal noise. The detector voltage output is contaminated with thermal noise. Thermal noise is usually considered as following the Gaussian distribution.

Figure 1 demonstrates the principle of threshold detection which is widely used in radar systems. Curve $P_0(y)$ is the probability density function of the voltage output when there is no target present. The mean of this probability density function is zero. Curve $P_1(y)$ is the voltage when there is a target present (Reference 1).

The decision threshold is determined by Neyman-Pearson criterion, which maximizes detection probability while keeping a constant false alarm rate. There are two kinds of errors. One is the false alarm. The false alarm probability is the area above the threshold under curve $P_0(y)$. The other is the probability of missed detection. Its probability is the area below the threshold under curve $P_1(y)$. For a constant false alarm rate detection using the Neyman-Pearson criterion, the density function without the presence of a target determines the threshold level. The density function with the presence of targets determines the missed-detection probability. The same applies in the detection of a target in clutter. Clutter is the unwanted back scattered signal from the sea surface. It is a coherent RF signal similar to the target return. Thus the integration techniques which are designed to increase the signal to thermal noise ratio can not be used against clutter. The clutter power is proportional to the illuminated area of a resolution cell of the radar.

Figure 2 is the geometry of a resolution cell. The illuminated area is the product of range, beam width, range cell and the secant of the grazing angle. The received power is directly proportional to the clutter cross section, sigma. The proportionality constant

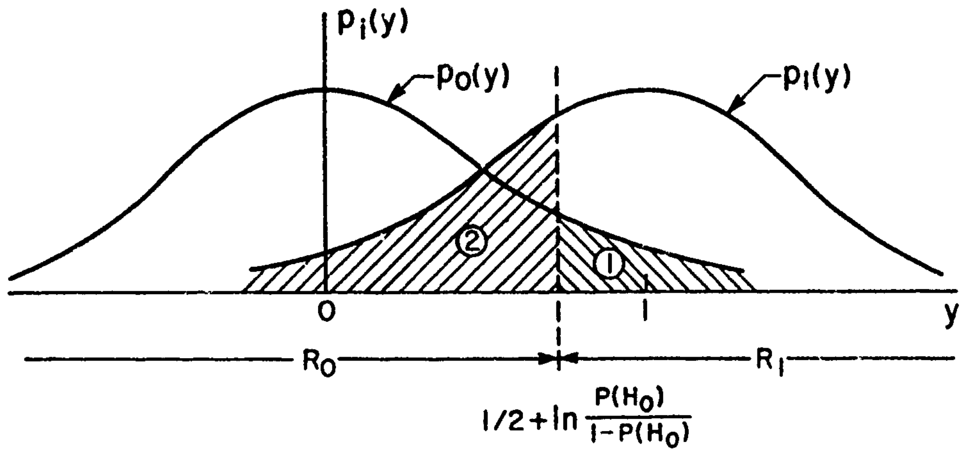

Figure 1. Decision Diagram in Gaussian Noise.

is a function of the space attenuation and antenna gain. Conventionally, the clutter reflectivity, which is the clutter cross section per unit area, is used. Note that the reflectivity, being a ratio of the cross sectional area to the illuminated area of the sea surface, is a dimensionless constant. At X-band if the range cell is greater than 20 m (Reference 1), the radar is considered as low resolution radar.

The radar signal is usually narrow band. Any narrow band signal may be expressed as $x(t)\cos\omega t + y(t)\sin\omega t$, where $x(t)$ and $y(t)$ are the I channel and Q channel signals. For a low resolution radar, the signals are scattered from a fluctuating surface of large illuminated area. By the central limit theorem, both the I channel and Q channel signals are Gaussian. The envelope detector output voltage, then, is Rayleigh distributed and is called Rayleigh clutter.

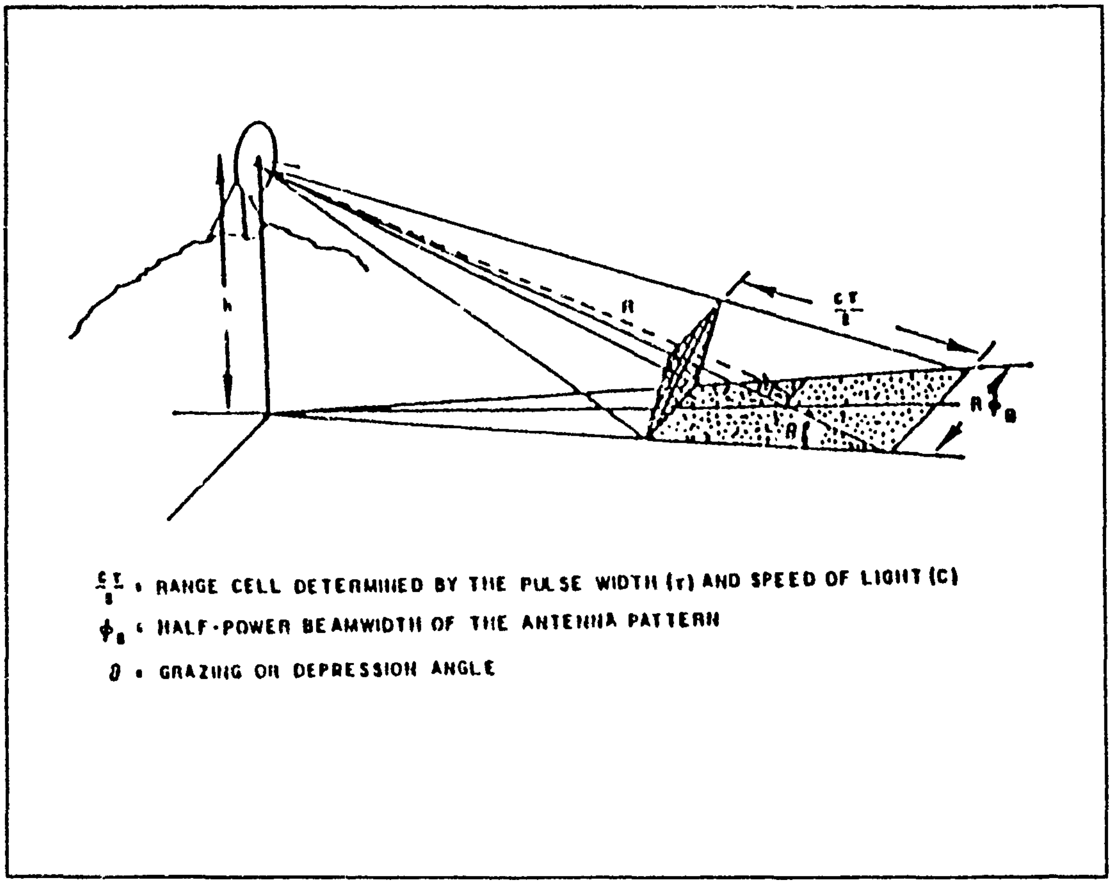

Figure 2. Geometry of Resolution Cell.

Modern radars have higher resolution. The reason is that by decreasing the illuminated area, they increase the signal to clutter ratio. The power scattered from a target remains constant if the target is in a resolution cell. The power scattered from the sea surface is reduced since the resolution cell is smaller.

It is observed though that, while the total back-scattered power from the sea surface is reduced, the peak power is not decreased and the clutter signal becomes spiky in appearance. Thus the false alarm rate is not reduced even though the clutter power is lower. Observations associate such spikey nature with the presence of whitecaps (Ref. 1).

Measured data show the reflectivity of breaking water to be about 1 to 1.5 while that of unbroken water is about -40 dB below unity (Ref. 1). Hence, when breaking waves are present, their back scattering is the major components of the sea clutter.

Furthermore, since the number of breaking waves within a resolution cell is limited, the central limit theorem does not apply to the clutter of a modern, high resolution radar. This may be the reason for the non-Rayleigh distribution observed in many measurements.

Figure 3 is one example of the non-Rayleigh sea clutter. Data obtained by NRL show that the distribution has a longer tail compared to the Rayleigh distribution (reference 8), which means there is a higher probability of stronger sea clutter. The simulation of this phenomenon has been carried out by Lewis and Olin (Reference 1) and will be discussed in chapter 2.

In the investigation of clutter distribution, many effects should also be considered. The reason that sea return is random is that the surface is fluctuating. Many researchers describe the water surface using the slope and height of the waves as the random variables. In terms of these random variables, the conditions for wave breaking can be stated as some breaking criteria (Reference 2) derived from ocean wave dynamics.

Chapter 3 provides a model for the back scattering from the sea surface. Since scattering is very different between broken and unbroken water waves, a breaking occurrence model is developed. Back scattering from unbroken water and from breaking waves are simulated separately and then combined afterward according to the positions and sizes of white caps at the sampling time.

Chapter 4 is the simulation of total back-scattering signal from the sea. In each simulation run of different parameters, 20,000 independent samples are calculated.They are used later to find the PDF of clutter voltage.

In Chapter 5, the PDF of the clutter voltage is calculated after combining back-scattering from whitecaps and unbroken water. The clutter voltage is truncated and divided into 500 equal intervals. The number of samples located in each internal divided by 20,000 is the probability of the clutter voltage occuring in this interval.

The simulated PDF is obtained by dividing the clutter voltage probability with the width of the interval.

The simulation result shows that clutter voltage from unbroken water fits well with a Rayleigh distribution if the randomness factor to be defined in Chapter 2 is 1. Otherwise it may be fitted with the Weibull distribution. This compares favorably with some measured data (Reference 3).

Clutter distribution from broken water has a new form. This thesis suggests that its shape depends on the sea state and the randomness factor of the white caps.

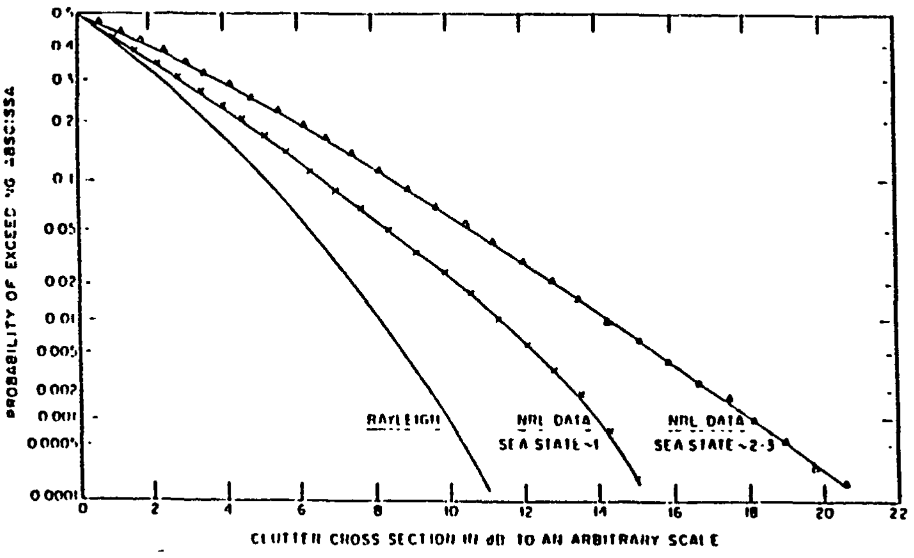

Figure 3. Experimental sea clutter cross section data taken by NRL on X band radar, 0.02 microsecond pulse, vertical polarization and 4.7 degree grazing angle, and Rayleigh distribution for comparison.

II. SCATTERING FROM A WHITECAP OR AN UNBROKEN SURFACE

A. BASIC THEORY

Calculating the backscattered signal from the sea surface involves a better understanding of ocean dynamics, beyond that which is currently available.

The goal for this thesis is to find a framework upon which measured parameters can be incorporated to provide a statistical description of the sea clutter. A model developed by Olin and Lewis is adopted to calculate the scattering from growing whitecaps. This model and its implemention are discussed in this chapter. In later chapters, this simple model is extended to include the spatial and temporal statistics of the breaking waves to obtain the PDF of the sea clutter. With the extended model, the spatial and temporal correlation of the clutter voltage can be investigated later.

Lewis and Olin's model is for the back scattered signal from a wave crest, including the white cap. In this model, a sea wave is divided into identical zones of a quarter radar wavelength each. Within each zone, the scattered field from the sea surface is roughly in phase and is considered to be due to a source located at the center of this zone. The relative magnitude of the back scattered signal from this zone is 1-kX and the phase is $2\pi kY$. Both X and Y are random variables uniformly distributed over 0 and 1. Therefore when k equals 1, the magnitude of the back scattering can vary over the complete range of 0 to 1 while the phase of the signal can vary over the complete range of 2π. This parameter k is called the "randomness factor" and the back scattering is completely random when $k = 1$. When k does not equal to unity, a nonfluctuating component in the back scattered signal is introduced. Thus k can be considered as a measure of the "roughness"(or lack of) of the wave.

Assume a radar is operating in X band with a 3 cm wavelength. Each quarter wavelength zone is .75 cm. The growth rate of a white cap is observed to be 1 m/sec. The time for each white cap to grow one zone larger is 0.75 milliseconds. This approximately agrees with the 1 millisecond decorrelation time observed. The whitecap grows linearly from length zero to 0.96 meter, when the number of zones grows from 0 to 128.

Consider only the case when the sea waves are moving toward the radar. The back scattered signal referred to the back edge of the white cap is

$$e_m = S_m \exp -j4\frac{\pi}{\lambda}[(m-1)\frac{\lambda}{4} + d_m] \qquad (1)$$

where :

$S_m \leq 1$ = equivalent zonal reflection coefficient.

$0 \leq d_m \leq \frac{\lambda}{4}$ = location of effective scatterer within the zone.

$$S_m = (1 - kX_m) \qquad (2)$$

$$d_m = \frac{\lambda}{8} + \frac{\lambda}{4}k(Y_m - \frac{1}{2}) \qquad (3)$$

where :

$0 \leq X_m \leq 1$ = random component in amplitude.

$0 \leq Y_m \leq 1$ = random component in phase.

$0 \leq k \leq 1$ = fraction of random component.

By using these expressions and shifting the initial reference surface by $\frac{\pi}{2}$, the scattered signal can be written:

$$e'_m = (-1)^{m-1}(1 - kX_m)\exp -j\pi k(Y_m - \frac{1}{2}) \qquad (4)$$

If the range extent of the whitecap is W, then the number of zones is $N = 4\frac{W}{\lambda}$, and the total backscattered signal Γ_N is given by

$$\Gamma_N = \sum_{m=1}^{N}(-1)^{m-1}(1 - kX_m)\exp -j\pi k(Y_m - \frac{1}{2}) \qquad (5)$$

where k is the randomness factor of the back scattered signal. It is assumed to be constant from zone to zone. Note that only the relative magnitude of the scattered signal is considered. The mean clutter voltage is determined from experimental measurement.

In order to model the growth of a white cap, D is introduced as the internal decorrelation time. Hence in each zone, the phase and amplitude of the scattered signal will be another pair of random numbers after the white cap grows by D quarter wavelength. For example, if D is 5, then in this thesis the phase and amplitude of scattering from effective scatterers in every zone of a growing whitecap will be another pair of random variables after 5 times 0.75 millisecond.

In the computer simulation of scattered signals from breaking waves, phases and amplitudes are generated from a uniform random number generator. The growth of a whitecap is described by increasing its zone number.

B. COMPUTER SIMULATION

The algorithm to simulate back scattering from one growing breaking wave is :

1 set whitecap size from 1 to 128,
2 call the uniform random number generator to get 2 random numbers for the phase and the amplitude for each zone,
3 sum the back scattered signal from all zones at the sampling times,
4 repeat for each sampling time, and then get the maximum value of samples and normalize all samples.

Since the scattered signal is time-dependent, it is not a stationary process. A FORTRAN subroutine is listed in Appendix A to simulate the scattered signals for one breaking wave growing process. The output of this subroutine is an array containing 128 scattered samples. The mean of each set of samples is different. But according to Lewis and Olin's measurement, the reflectivity of a breaking wave is about 1 to 1.5 (dimensionless or M**2/M**2). We choose a value of 1.5 as the reflectivity of the whitecaps. The mean clutter cross section is known to be the reflectivity times the whitecap area.

The clutter voltage is 1.224745 So in the simulation, the 128 samples are first normalized by the maximum sample value. Then they are scaled by 1.224745 as the mean of the samples. Figure 4 is a set of data measured by Lewis and Olin. It shows the clutter cross section from a single resolution cell. A modulation imposed on the signal is evident which is attributed to the intermittancy of the breaking waves (Reference 3).

Figure 5 is a realization of this model with $k=1$ and $D=1$ from one breaking process. Figure 6 is a realization with $D=1$ and $k=0.8$, Figure 7 with $D=1$ and $k=0.1$. there is little modulation on samples of small zone numbers. Figure 8 is a simulation with $D=1$, $k=.06$ and modulation becomes more obvious, Figure 9 is with $k=1$ and $d=5$ and shows wider fluctuation.

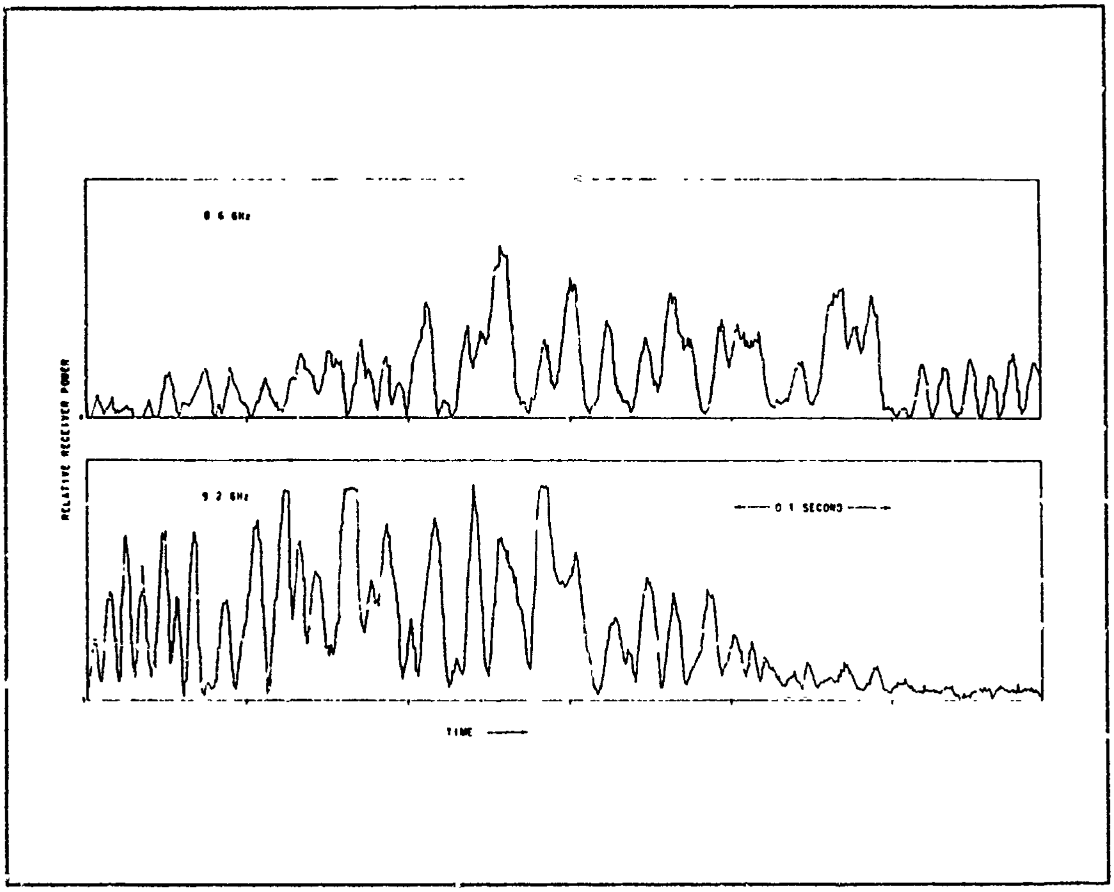

Figure 4. Time history of clutter cross section measured by Olin and Lewis

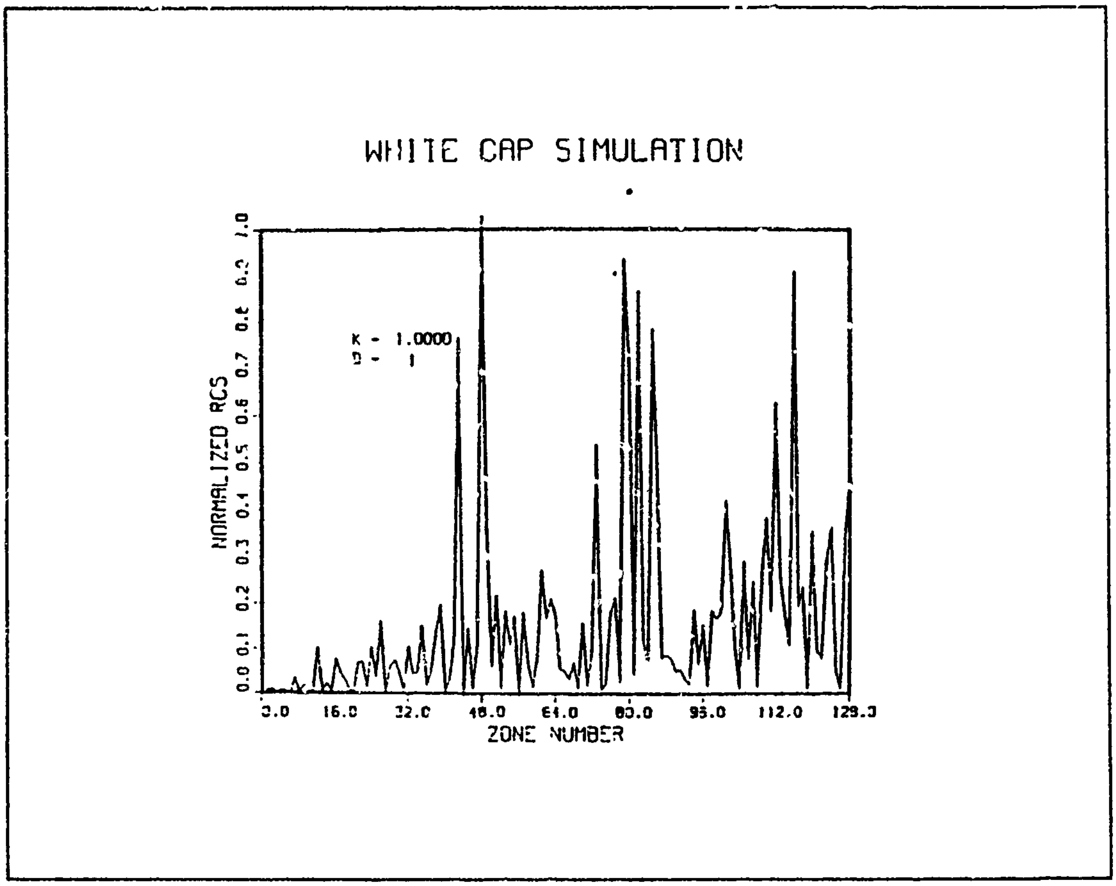

Figure 5. Simulated scattered signal from whitecap, D = 1, k = 1.

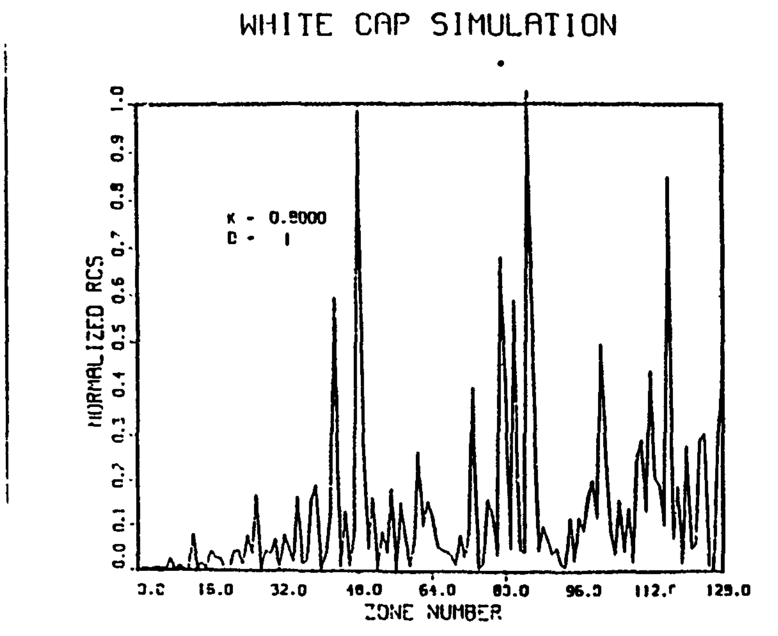

Figure 6. Simulated scattered signal from whitecap, D = 1, k = 0.8

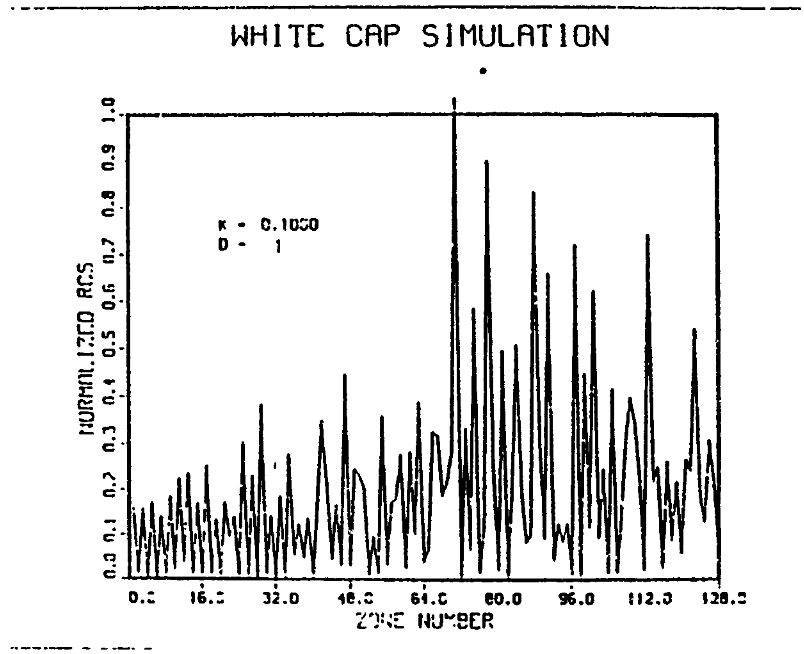

Figure 7. Simulated scattered signal from whitecap, D = 1, k = 0.1.

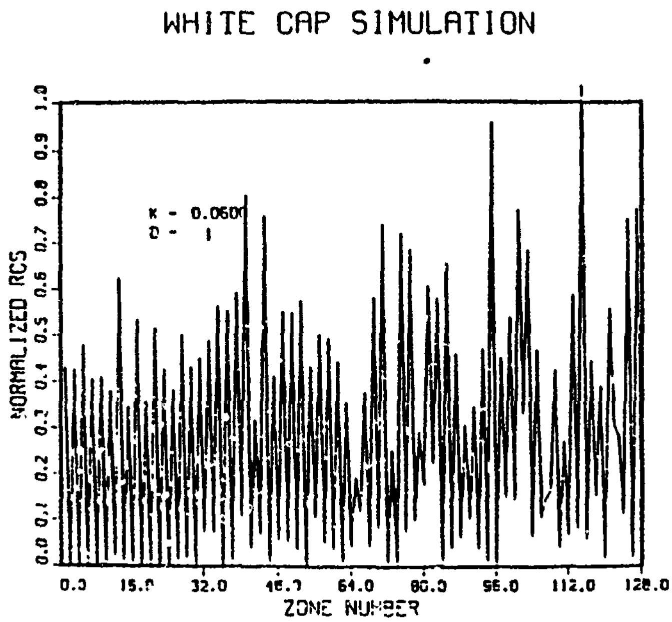

Figure 8. Simulated scattered signal from whitecap, $D = 1$, $k = 0.06$.

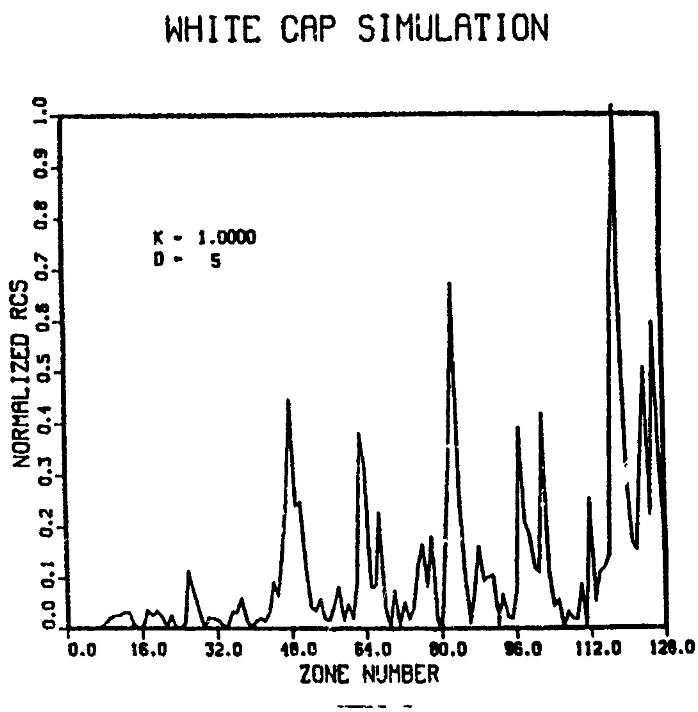

Figure 9. Simulated scattered signal from whitecap, D = 5, k = 1.

The same model is also used in simulating the scattering from the unbroken water. The difference is that the area of the unbroken water is the whole resolution cell. This is a rectangle of 225 square meters. The range cell is 15m for a pulse width of 100 nanoseconds. The range cell contains 2000 zones, each zone has a length of 0.75 cm. Each clutter sample is the sum of scattered signals of 2000 terms. In the simulation, the uniform random number generator is called 2000 times to generate random phases and amplitudes. There is no growing effect in the unbroken water.

C. AUTOCORRELATION

Because of the growth of whitecaps, the clutter voltage is not a stationary process. The number of terms is changing, so it is not expected to have the same autocorrelation function.

Figures 10 to 16 are autocorrelation functions with different randomness factors and internal decorrelation times.

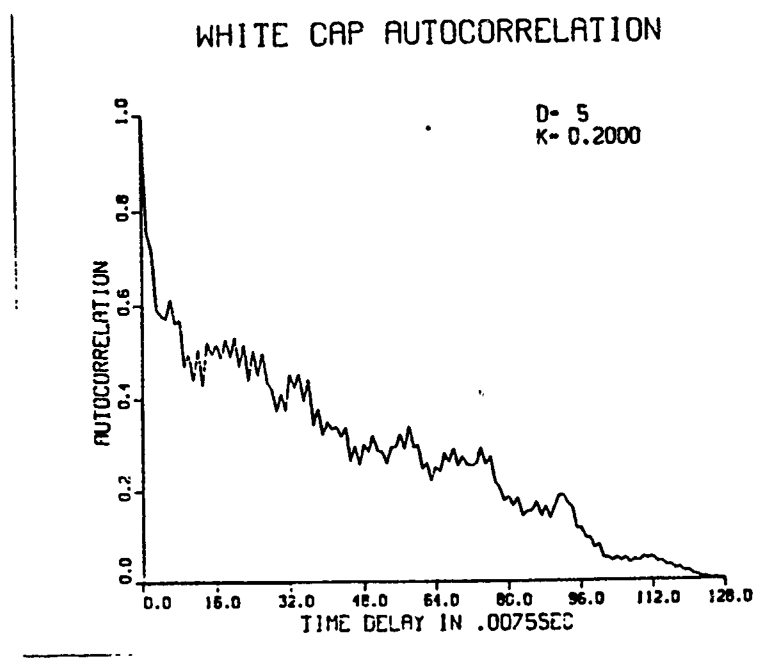

Figure 10. Autocorrelation function of scattering from whitecap, D = 5,k = 0 .2.

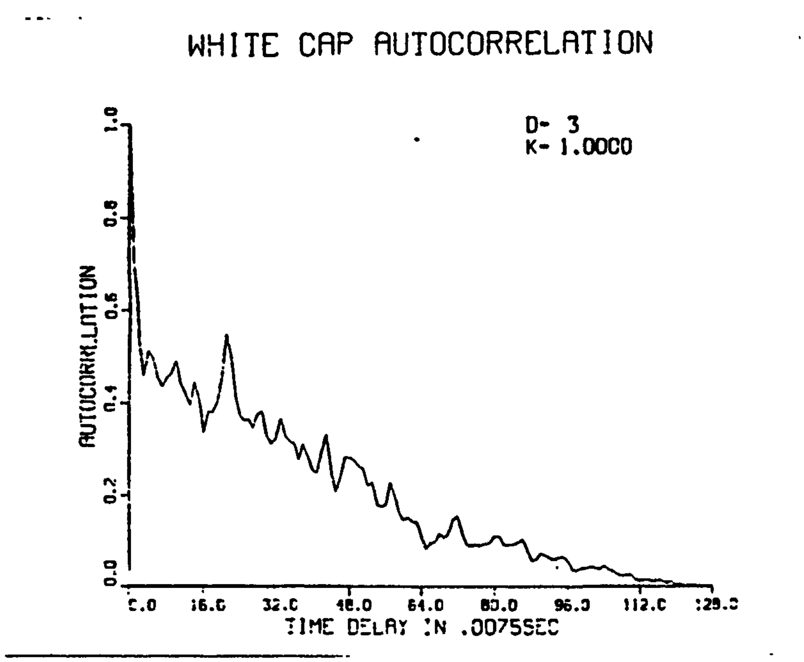

Figure 11. Autocorrelation function of scattering from whitecap, D = 3,k = 1

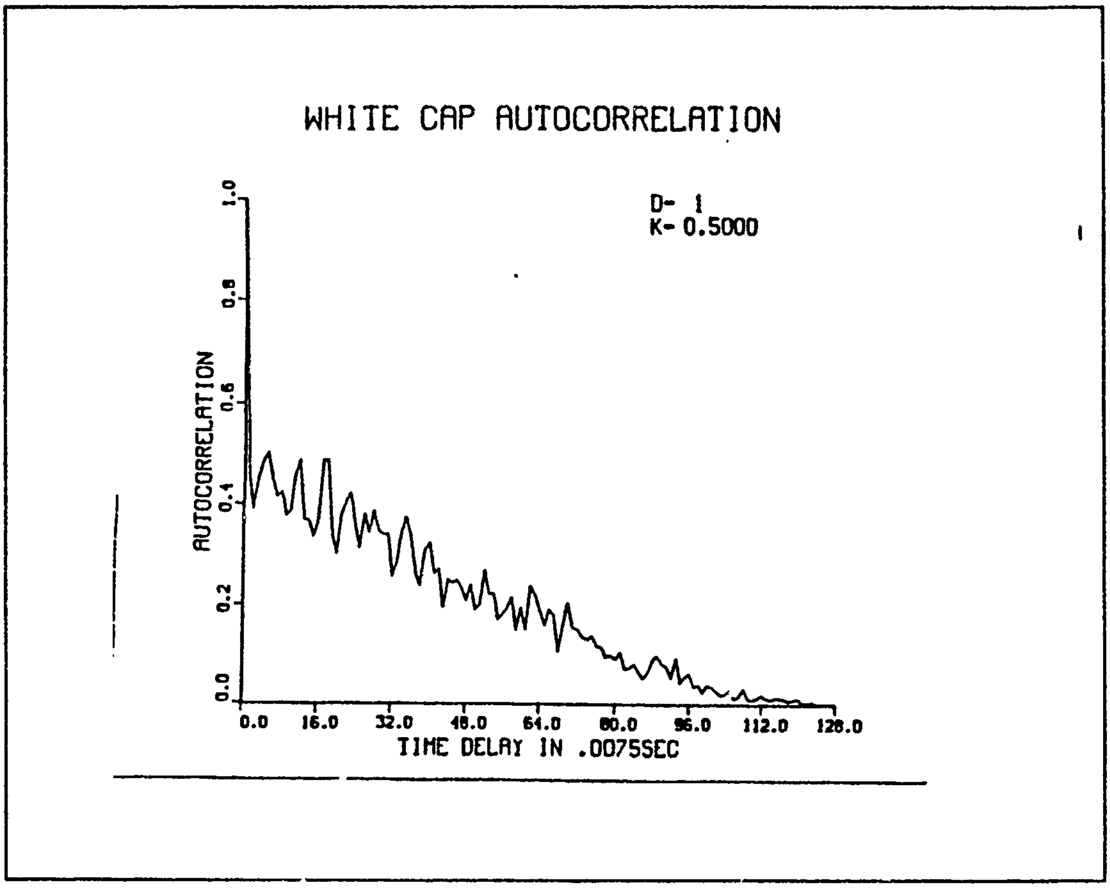

Figure 12. Autocorrelation function of scattering from whitecap, D = 1, k = 0.5.

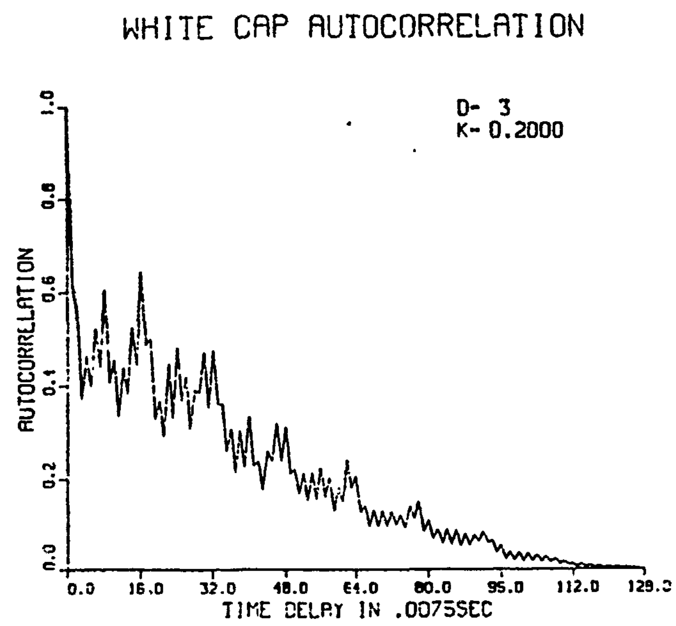

Figure 13. Autocorrelation function of scattering from whitecap, D = 3, k = 0.2.

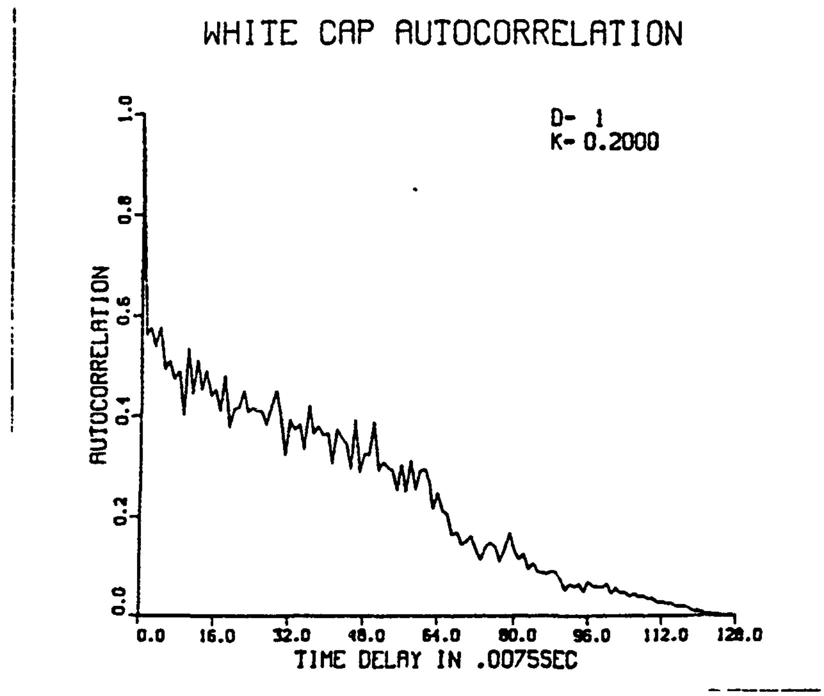

Figure 14. Autocorrelation function of scattering from whitecap, D = 1, k = 0.2

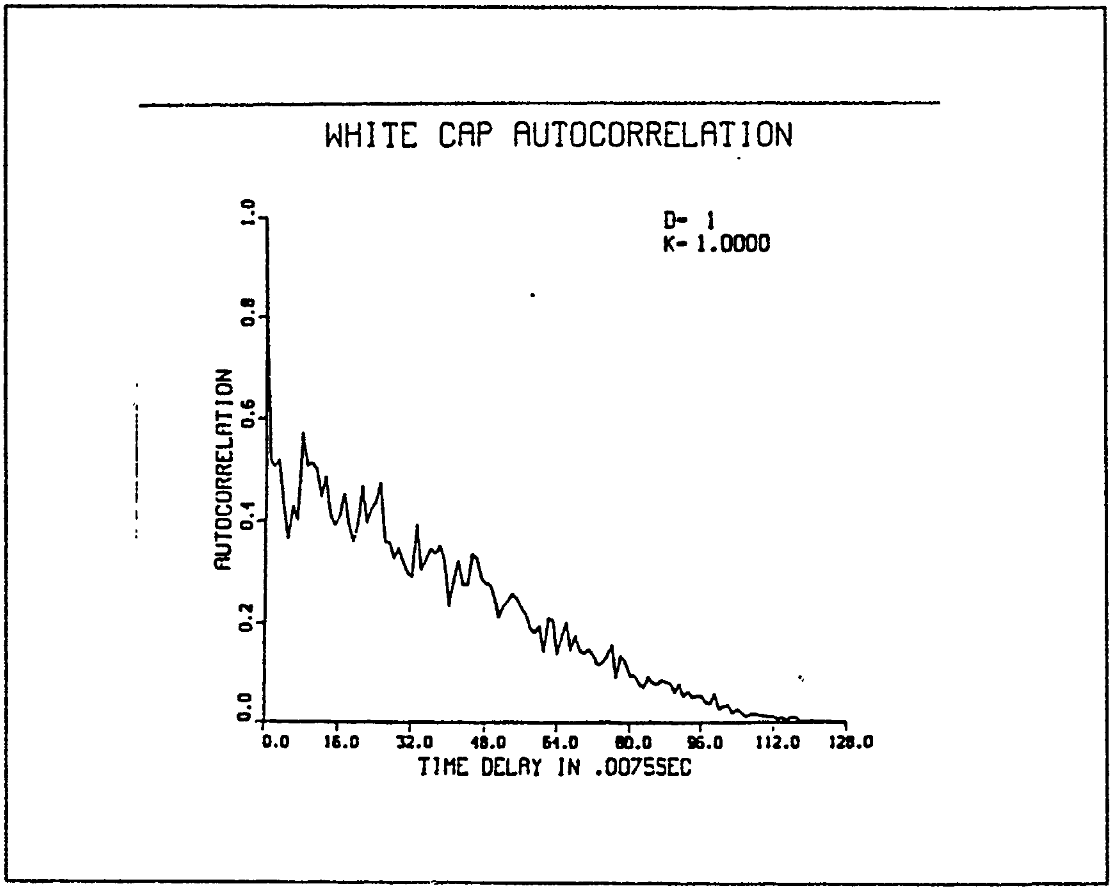

Figure 15. Autocorrelation function of scattering from whitecap, D = 1,k = 1

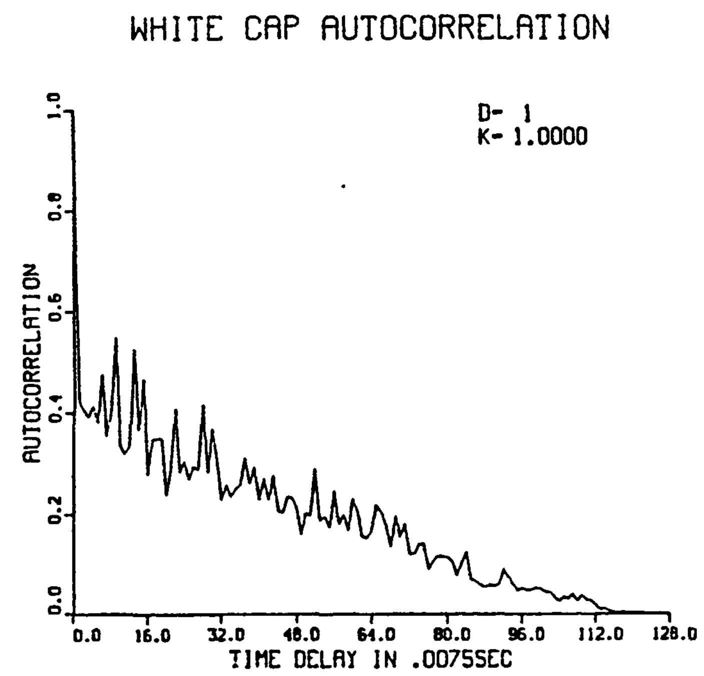

Figure 16. Autocorrelation function of scattering from whitecap, D = 1,k = 1 , seeds of random number generators are different from seeds in Figure 15

D. PROBABILITY DENSITY FUNCTION

It is well known that the clutter from a large observed area obeys the Rayleigh distribution. The scattering model developed above is used to simulate the scattering from unbroken water. It is clear from the results of this section that the probability density function of such clutter cross section is an exponential distribution. Thus the model is verified for this particular case.

There are 2000 independent samples simulated to calculate the probability density function of clutter cross section from an unbroken water. The result shows that when the randomness factor k is 1, the probability density function of the clutter cross section is an exponential distribution, while the clutter voltage is a Rayleigh distribution.

Figure 17 and 18 are PDFs with $k = 1$. The dots are calculated PDF from the samples. The average of these samples is used to plot the theoretical distribution of clutter cross section, which is the solid line. They are both exponential distributions. So the scattering model developed by Olin and Lewis is valid for unbroken water if the randomness factor is 1. Figures 19 and 20 are RCS distributions with a randomness factor of 0.3.

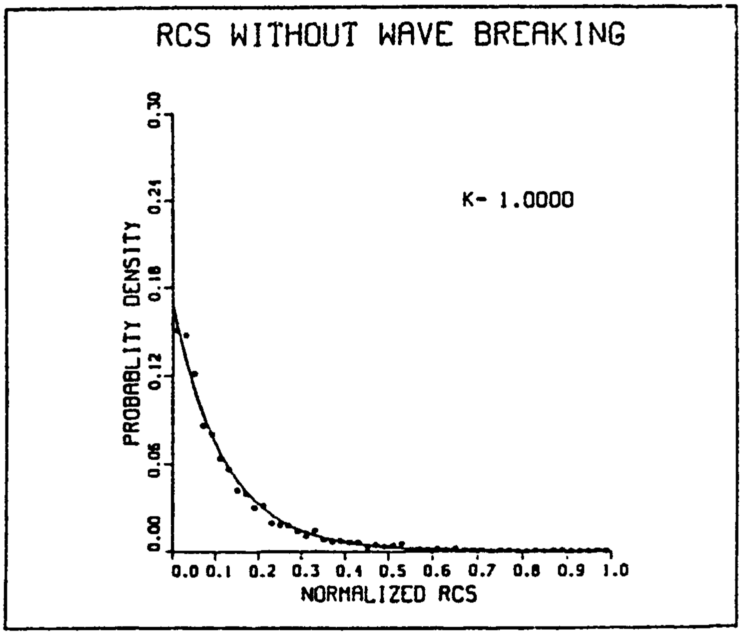

Figure 17. Probability density function of sea clutter cross section, randomness factor = 1.

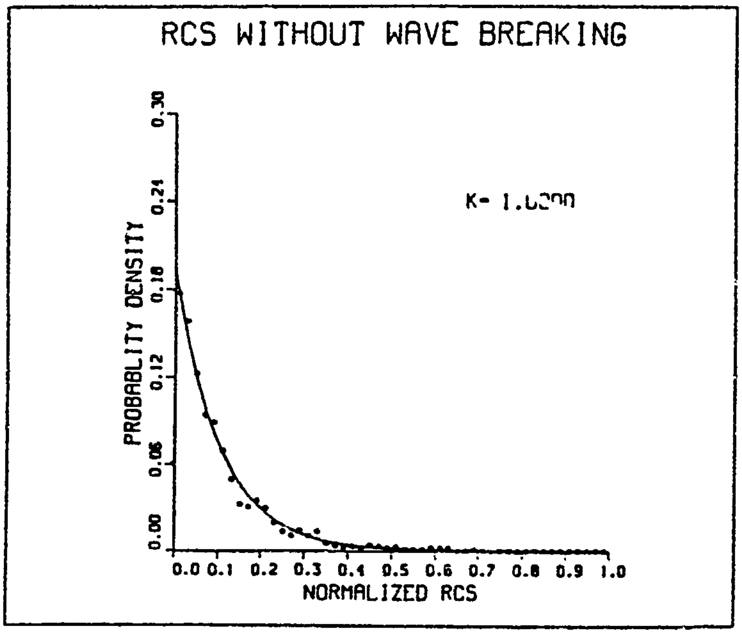

Figure 18. Probability density function of sea clutter cross section, randomness factor = 1. Seeds of random number generators are different from seeds in Figure 17.

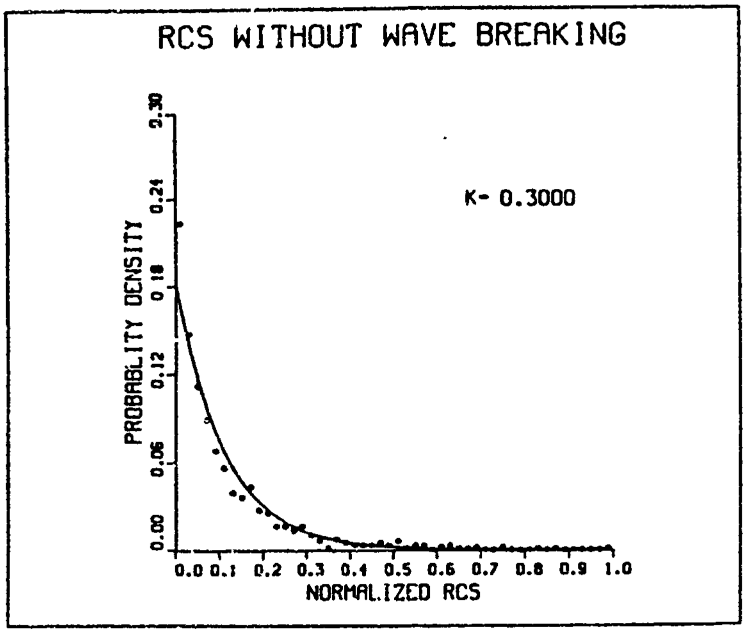

Figure 19. Probability density function of sea clutter cross section, randomness factor = 0.3.

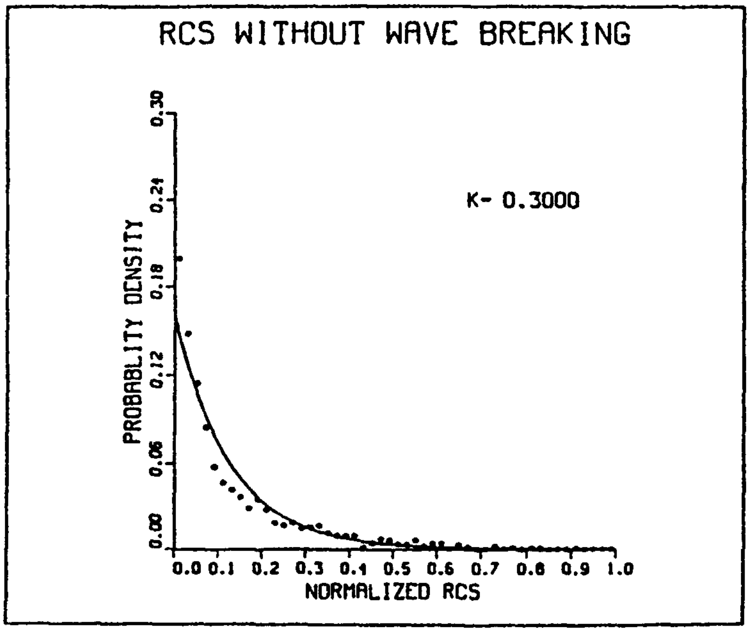

Figure 20. Probability density function of sea clutter cross section, randomness factor = 0.3.

Figures 21 and 22 are PDFs with randomness factors of 0.01. They deviate from an exponential distribution more significantly. Because the scattering model for unbroken water is verified to agree with the scattering of Rayleigh clutter if the randomness factor is 1, it is not necessary to sum up all 2000 terms for every sample. The Rayleigh random generater can be used and its mean is to be scaled by the unbroken water reflectivity.

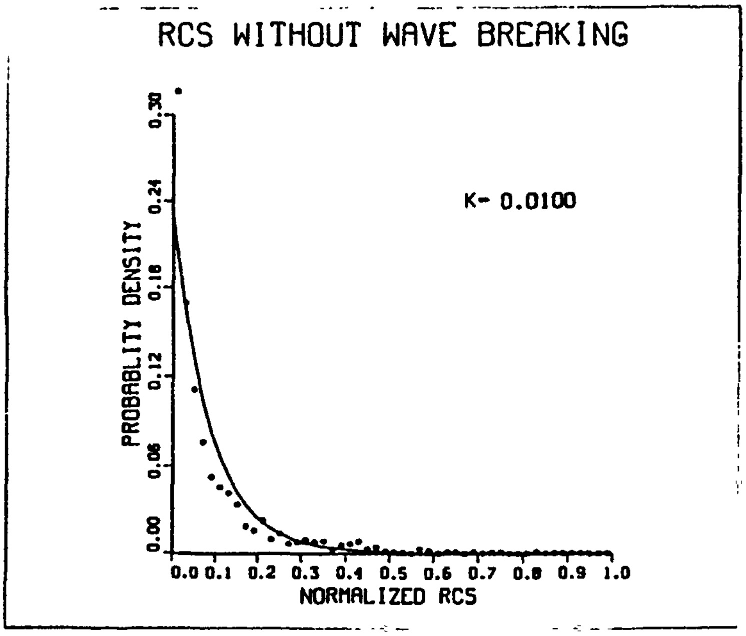

Figure 21. Probability density function of sea clutter cross section, randomness factor = 0.01.

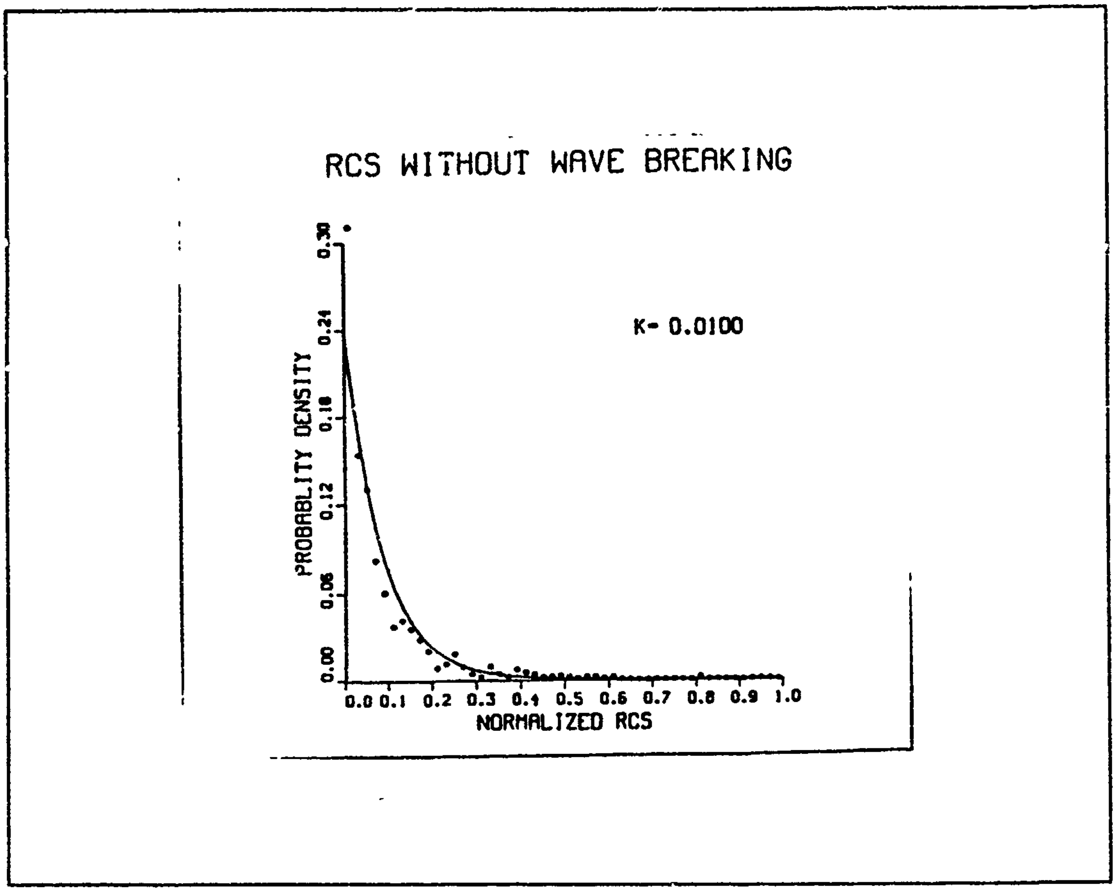

Figure 22. Probability density function of sea clutter cross secti` `. randomness factor = 0.01.

III. A SEA SURFACE MODEL

In Chapter 2, the scattering model simulates back scattered signals from the unbroken water surface and the individual breaking wave separately. Since, at any sampling time, there will be some breaking waves in the radar illuminated area, the locations and sizes of whitecaps must be modeled and combined with the unbroken sea surface to calculate the total backscattered signal.

In this chapter, a sea surface model is developed to simulate the occurrence of whitecaps in the resolution cell.

A. OCCURRENCE OF WHITECAPS

It is known that the occurrence of a white cap is due to the interaction of wind and long ocean waves. When the wind blows, the capillary waves are formed and superimpose themselves on the long, faster waves. When the combined velocity of water waves on top of the long waves attains a kinetic energy beyond the surface tension potential, the water breaks away from the surface. This process is analogous to shot noise; when a kinetic energy threshold is reached, an electron breaks away from the metal surface and creates shot noise in the circuit.

Thus to describe the temporal occurrence of a breaking wave at a location, the Poisson distribution is adopted. Since the occurrence and kinetic energy of the capillary wave depend on the wind velocity, the average rate of the occurrence of the wind velocity will be given later in this chapter. The position of each breaking wave is assumed to be two dimensional, uniformly distributed, over the resolution cell.

B. COMPUTER SIMULATION

In this section, a FORTRAN subroutine listed in Appendix B is discussed The purpose of this subroutine is to simulate the occurring times and locations of breaking waves. The total observing time interval was 750 seconds. A Poisson random number generator is used to simulate a sequence of breaking wave occurrence times.

A uniform random number generator was used to simulate the locations of breaking waves. The illuminated area was 225 square meters and was divided into nine square sub-areas. In each sub-area the occurring times and locations of whitecaps were simulated independently.

The procedure of this simulation is to call the Poisson random generator to get a sequence of starting times over the entire observation period. Each starting time is the beginning of one breaking wave. For each whitecap, the uniform random number generator is called twice to get the X position and the Y position for each whitecap. This procedure is done nine times independently for the nine subareas. The nine sequences of occurring times are sorted and put into an array. Two other arrays are used to store the X and Y positions of the whitecaps corresponding to each of the occurring time sequences.

At any sampling time, the existing whitecaps are those with occurring times leading the sampling time by no more than 0.96 seconds. The time differences are the sizes of existing whitecaps since the growth of whitecaps is assumed to be linear.

Figure 23 to Figure 34 are consecutive samples of the observed area over one hundred samples, with a randomness factor of 0.9. The sampling time increment is 0.2 seconds. The time period is from t = 25.4 seconds to t = 27.6 seconds.

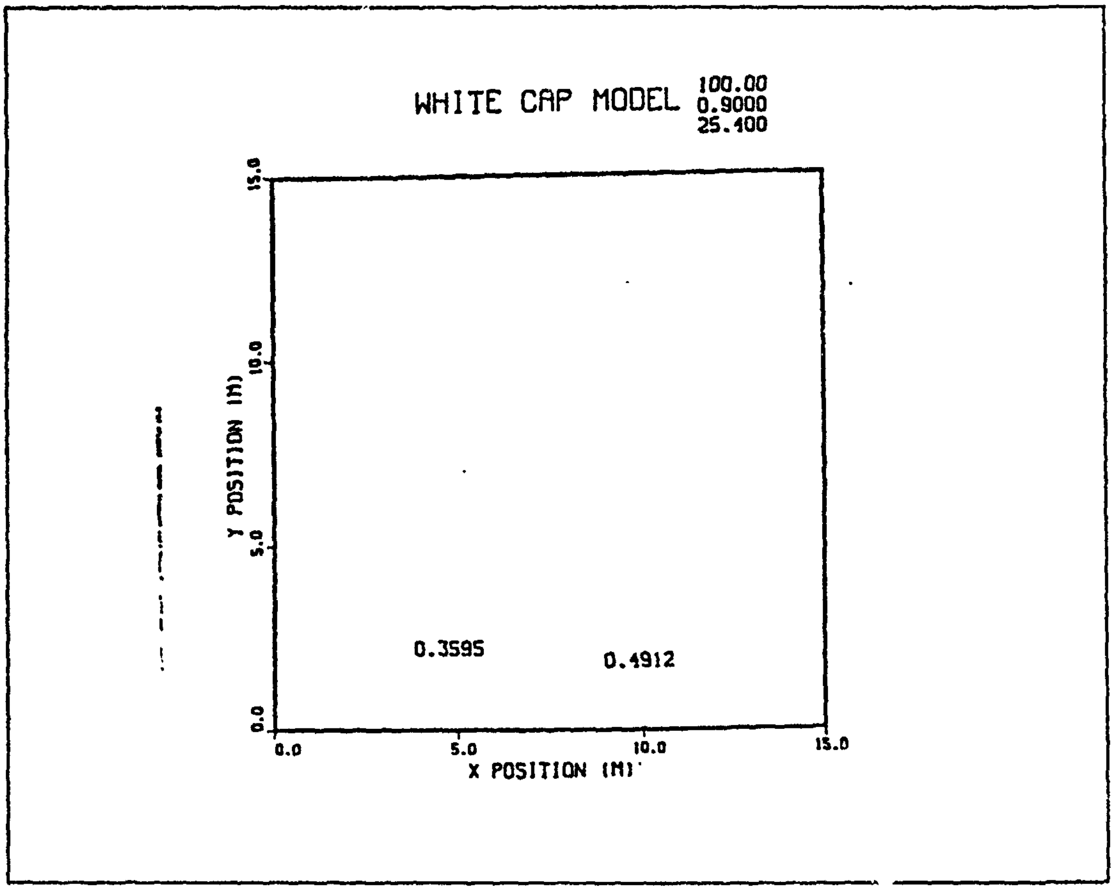

Figure 23. Whitecaps occurrence realization, total observation time 100 seconds, randomness factor = 0.9, sample time at 25.4 second.

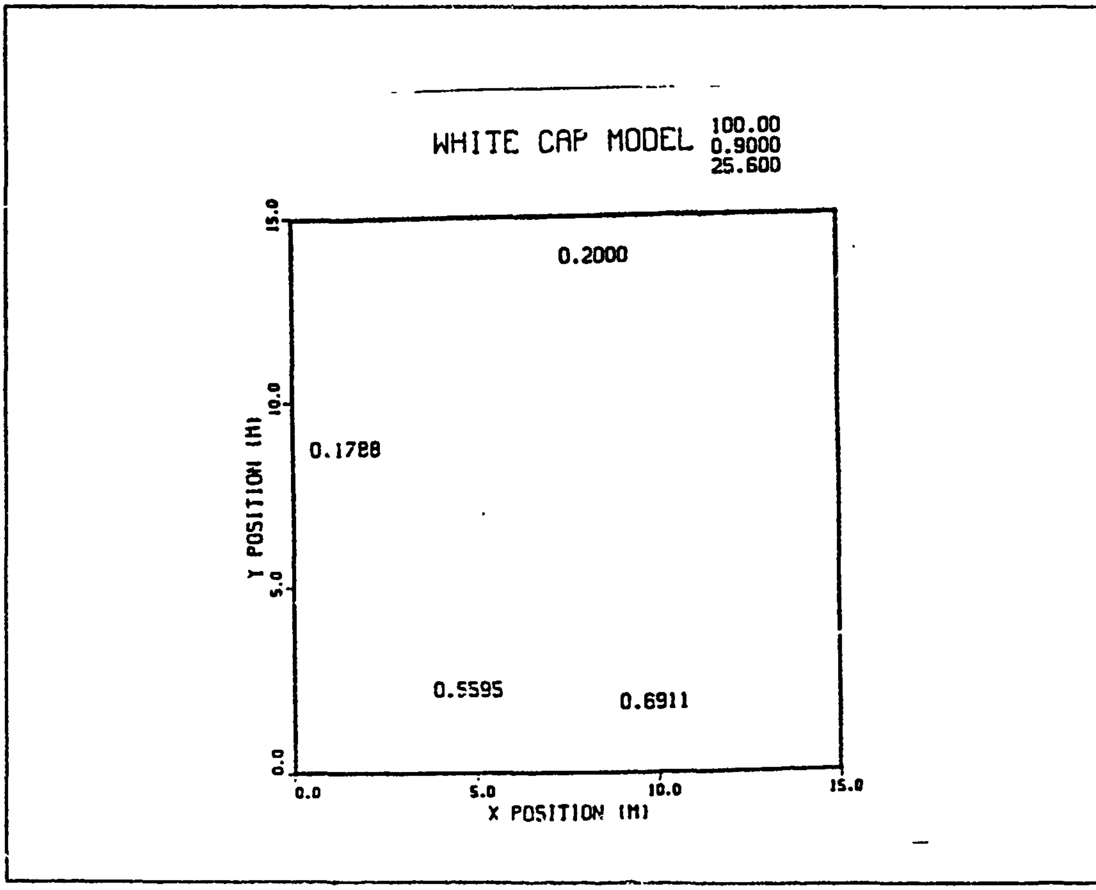

Figure 24. Whitecaps occurrence realization, total observation time 100 seconds, randomness factor = 0.9, sample time at 25.6 second.

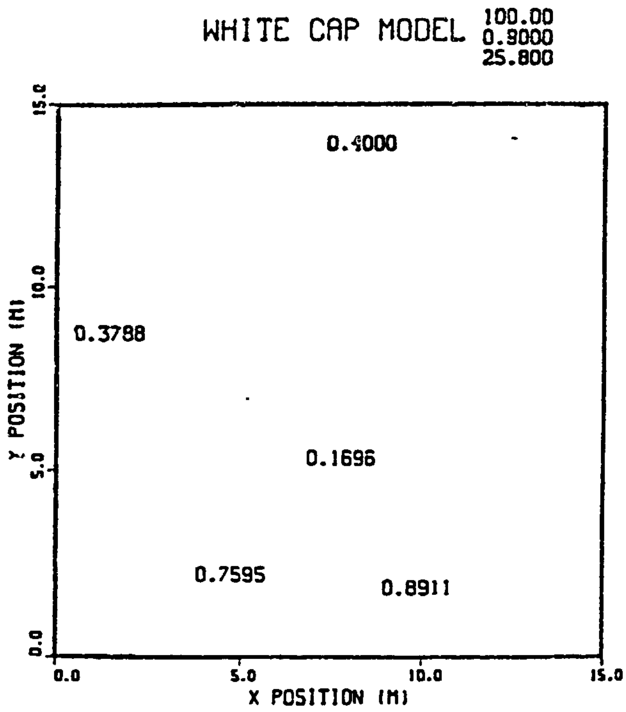

Figure 25. Whitecaps occurrence realization, total observation time 100 seconds, randomness factor = 0.9, sample time at 25.8 second.

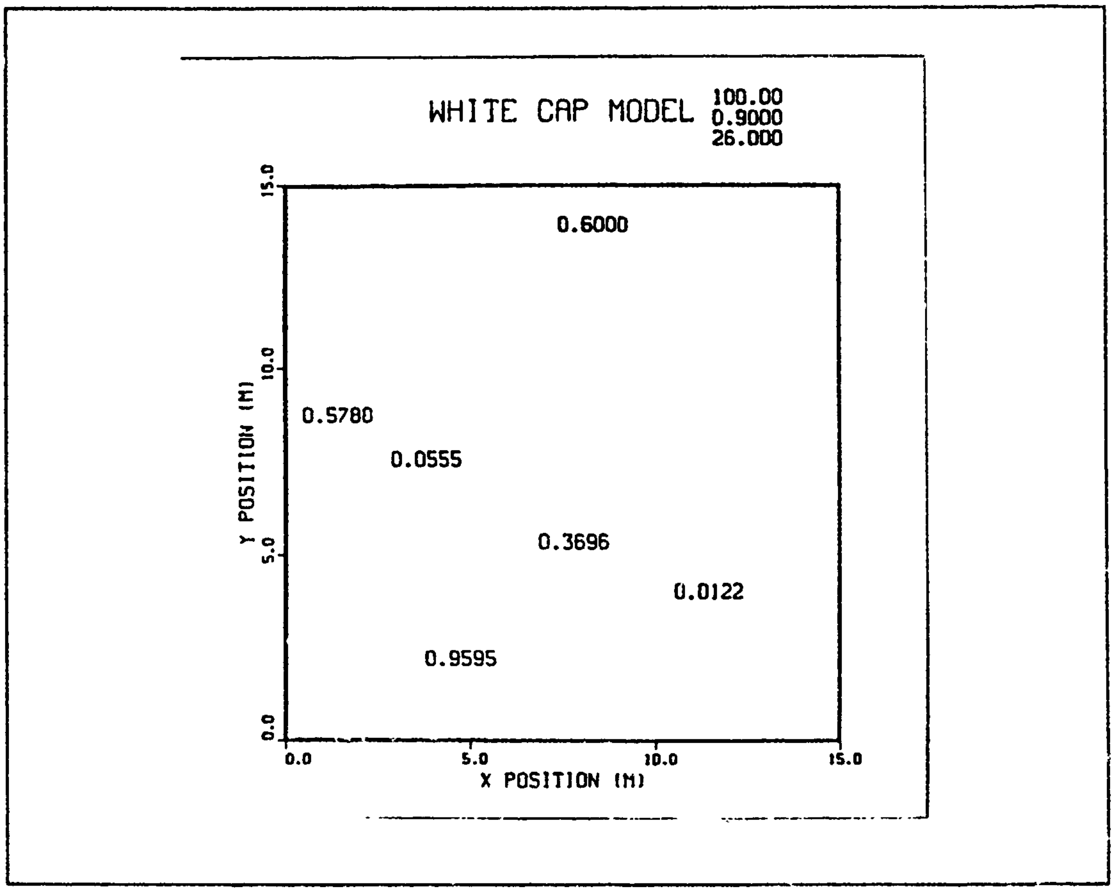

Figure 26. Whitecaps occurrence realization, total observation time 100 seconds, randomness factor = 0.9, sample time at 26.0 second.

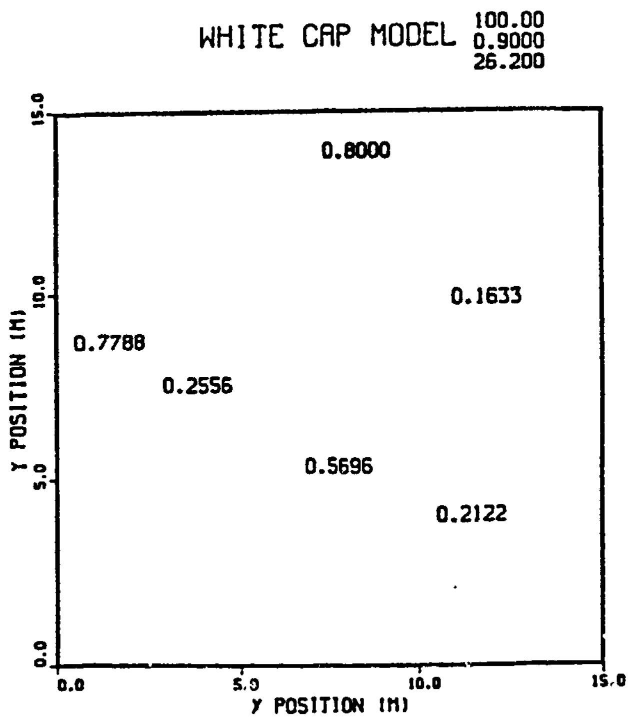

Figure 27. Whitecaps occurrence realization, total observation time 100 seconds, randomness factor = 0.9, sample time at 26.2 second.

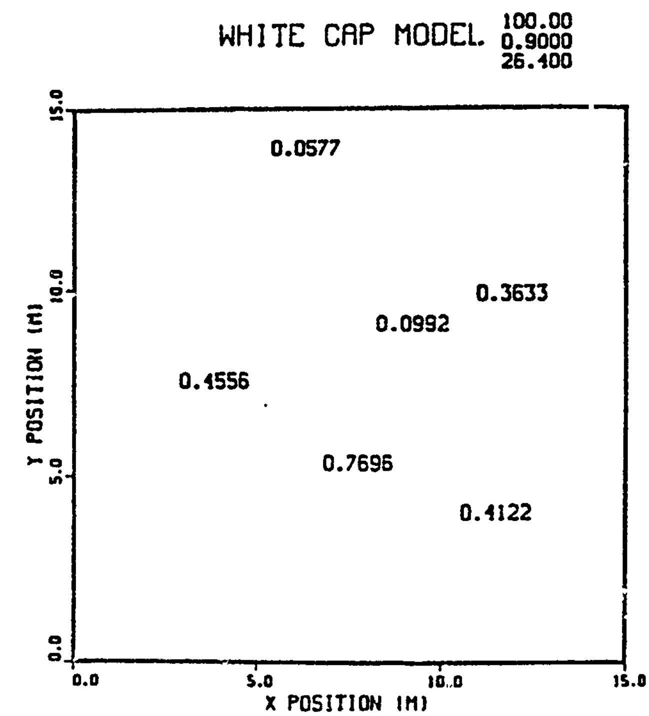

Figure 28. Whitecaps occurrence realization, total observation time 100 seconds, randomness factor = 0.9, sample time at 26.4 second.

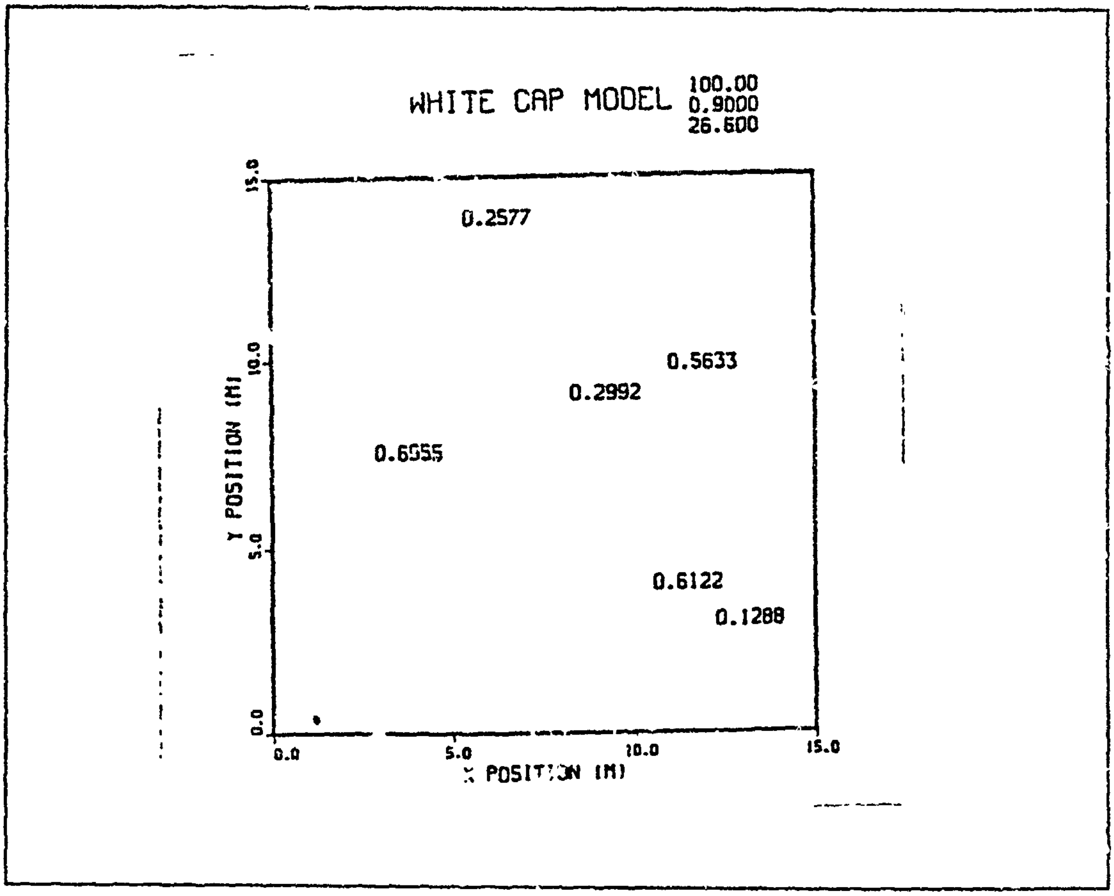

Figure 29. Whitecaps occurrence realization, total observation time 100 seconds, randomness factor = 0.9, sample time at 26.6 second.

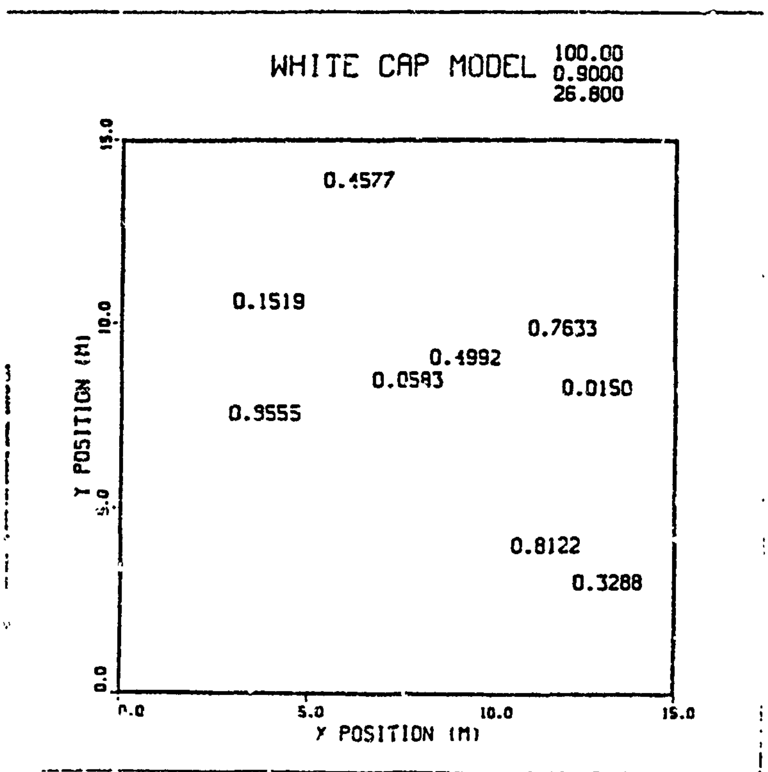

Figure 30. Whitecaps occurrence realization, total observation time 100 seconds. randomness factor = 0.9, sample time at 26.8 second.

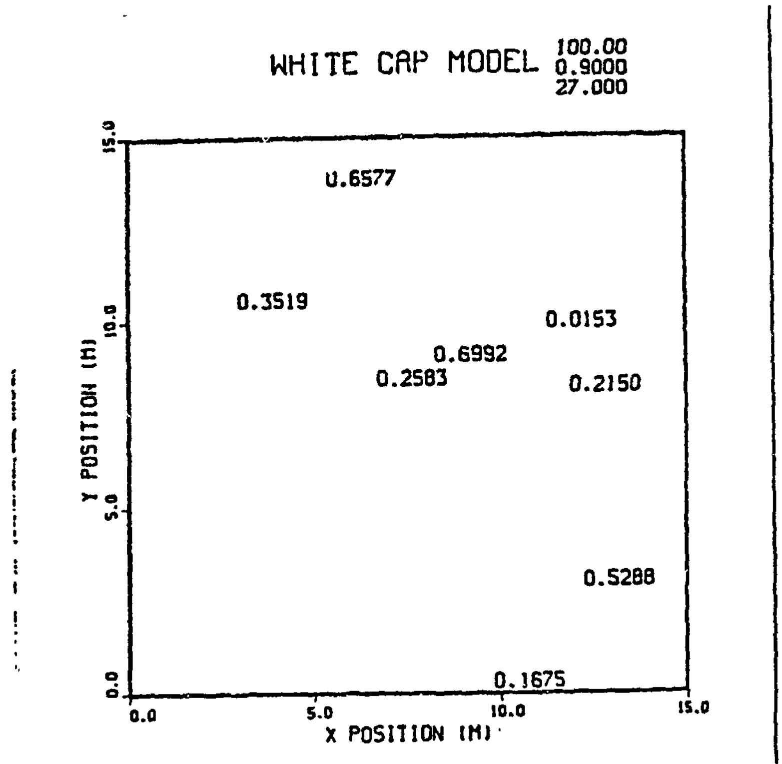

Figure 31. Whitecaps occurrence realization, total observation time 100 seconds, randomness factor = 0.9, sample time at 27.0 second.

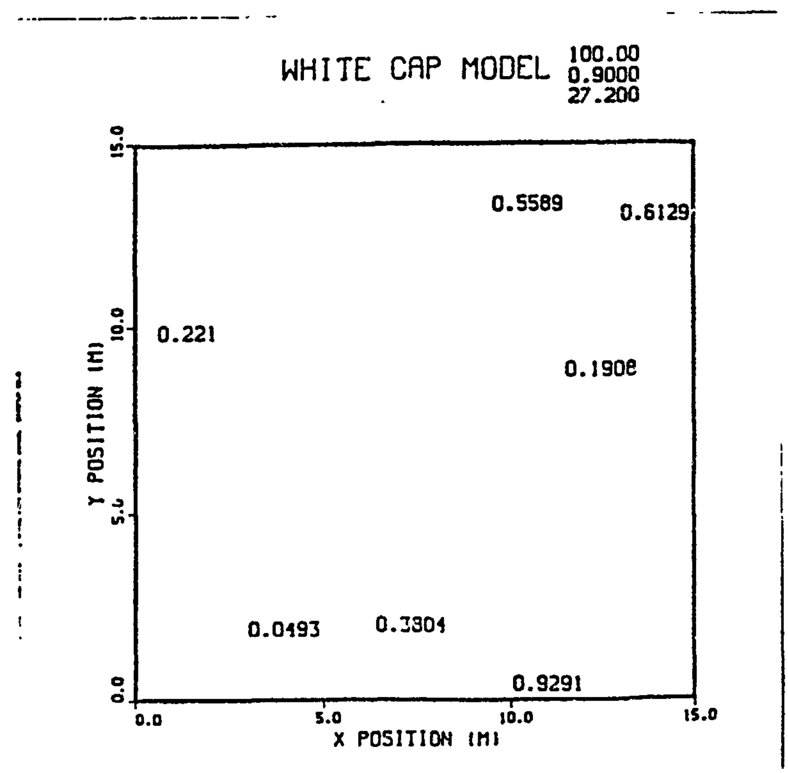

Figure 32. Whitecaps occurrence realization, total observation time 100 seconds, randomness factor = 0.9, sample time at 27.2 second.

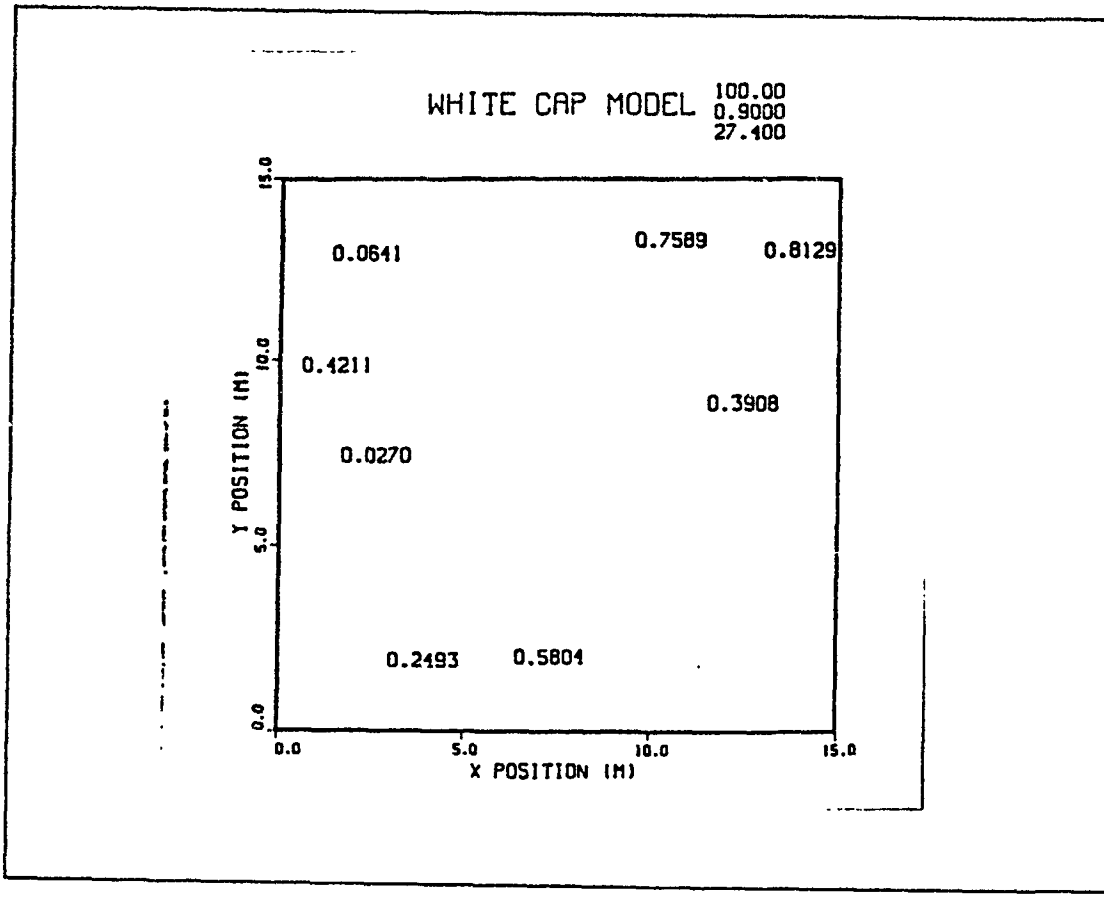

Figure 33. Whitecaps occurrence realization, total observation time 100 seconds, randomness factor = 0.9, sample time at 27.4 second.

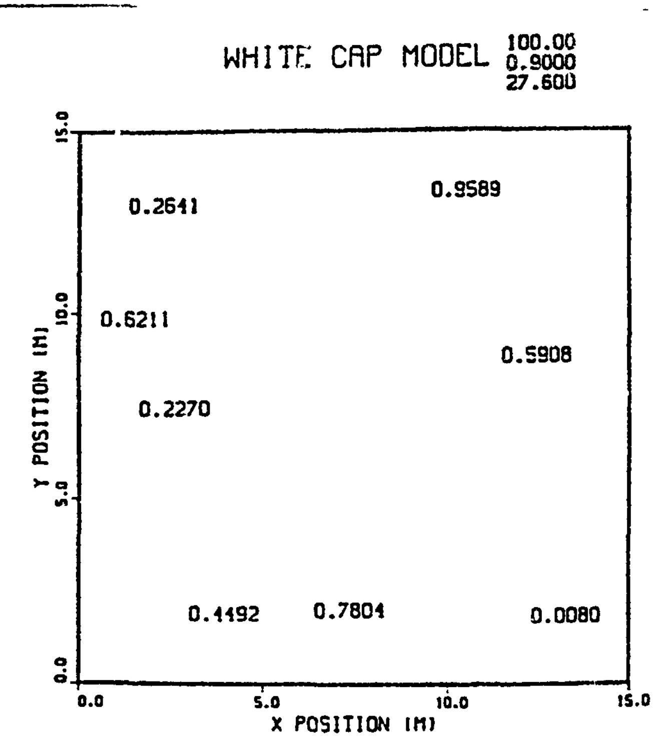

Figure 34. Whitecaps occurrence realization, total observation time 100 seconds, randomness factor = 0.9, sample time at 27.6 second.

Note that all whitecaps remain at the same locations with their sizes increasing linearly with time. When the size of a white cap reaches its full size of 128 zones, it disappears.

The rate parameter of the Poisson process are related to the sea state. Monahan and O'Muircheartaigh (Reference 5) conclude empirically that the whitecap coverage are related to the wind speed by the following equations.

$$W = 2.95 \times 10^{-6} \times U^{3.52} \qquad (6)$$

or

$$W = 3.84 \times 10^{-6} \times U^{3.41} \qquad (7)$$

where U is wind speed in meters per second, and W is the fraction of the sea surface covered by white caps.

The first equation is derived by the least-squares fitting of measured data. The second equation was derived using the robust biweighted fitting from the same data set. There are many other mechanisms affecting the local wave energy density, such as wave current interactions at the strong current boundaries, sea surface boundary stability and the pre-existing sea state (Reference 6).

At every sampling time, all sizes of the existing whitecaps are known. So the average coverage percentage of the sea surface can be computed over all samples.

The motion of wave is not modeled, because the velocity of the wave is assumed to be constant. Over any time delay, the difference in locations of existing whitecaps is constant. Then the motion contributes to an overall phase shift which does not affect the total scattered signal.

IV. TOTAL BACK SCATTERING SIGNAL

In this chapter, the complete simulation program is developed to calculated a sufficient number of back scattered signals from the illuminated area containing whitecaps. Then the probability density function of clutter voltage is calculated as a function of various parameters.

In previous chapters, a whitecap occurrence model was used to simulate the wave breaking process in one resolution cell. The illuminated area is 15 m by 15 m. The entire observation time is 750 seconds. A Poisson random number generator generates a sequence of starting times and a uniform random number generator generates the locations of each whitecap. These locations are the reference locations for the backscattering simulation and are assumed to be static since the wave motion contributes no relative phase shift in the scattered signal, if the velocity of the wave is constant. It is assumed that every whitecap has a full size of 0.96 m, a width of 1 m, and is breaking toward the radar receiver.

The size of a whitecap is assumed to be growing linearly at a rate of 1 m/sec. To calculate the total scattered signal at any time, the back scattered field from the unbroken water surface has to be combined with the contributions from the white caps over the illuminated area.

These white caps are at different stages of breaking and have different sizes. Each size determines the sample number in the corresponding 128 scattering samples over the life of a white cap The reference location of the unbroken surface is chosen to be the outer boundary of the resolution cell.

The reference location of the scattered field from a breaking wave is where the wave breaking begins. So in summing these scattered fields in complex numbers, it is necessary to align them to the same outer boundary of the resolution cell. This is done by shifting the phase of each scattered signal according to the distance of the whitecap to the outer boundary of the resolution cell.

Before summing the scattered signals, since they are all normalized sequences of samples, the mean strength of the unbroken water is scaled by 0.15 m. The reason is that according to actual observations, reflectivity of the unbroken water is -40 db below unity, or 0.0001. The clutter cross section is then 0.0001 times the area illuminated. So the RCS due to the unbroken surface is 0.0225 m**2. Taking the square root, the clutter voltage is a normalized 0.15.

The scattered signal from whitecaps is normalized at 1.224745 because a breaking wave's reflectivity is about 1.5. The area of one whitecap is 1 square meter, so each one has a clutter cross section 1.5 square meter. The clutter voltage is the square root of clutter cross section, so it is normalized at 1.224745 (Reference 1).

After shifting the phase, all scattered signals are summed to give the total back scattered signal. Its amplitude is the clutter voltage. The clutter cross section due to the particular normalization adopted in this thesis, is the square of this voltage, in square meters. In every run of this simulation, 20,000 samples are calculated.

A voltage range is selected that can cover all the samples. Dividing the range into 500 intervals and counting the number of samples locate in each interval and then dividing by 20,000, one gets a result which is the probability of the occurrence of clutter voltage within this interval.

The probability density at the center of each interval is the probability of the random variable within that interval divided by the width of the interval, if the interval is small enough.

V. PROBABILITY DENSITY FUNCTION

In this chapter, probability density functions of different randomness factors and internal decorrelation times are discussed.

The parameters in the simulation developed above include an internal decorrelation time in the growing process of whitecaps, a randomness factor representing roughness of whitecaps, and a Poisson process rate parameter, which determines the number of breaking waves. When wind speed is very small, a small occurrence rate causes no wave breaking over the entire observation time.

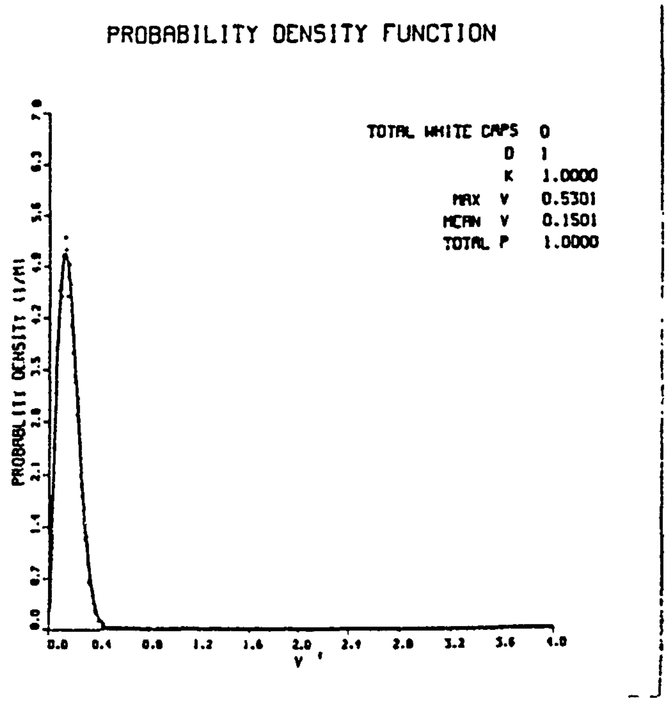

Figure 35. Comparison of PDF between simulation and Rayleigh distribution.rate = 0.0001, observing time = 750 seconds, total whitecaps = 0.

Figure 35 shows the comparison between simulated probability density function of the clutter voltage and theoretical Rayleigh distribution when the water is unbroken.

The dotted line is result of the simulation; the solid line is the Rayleigh distribution with the mean equal to the simulated result.

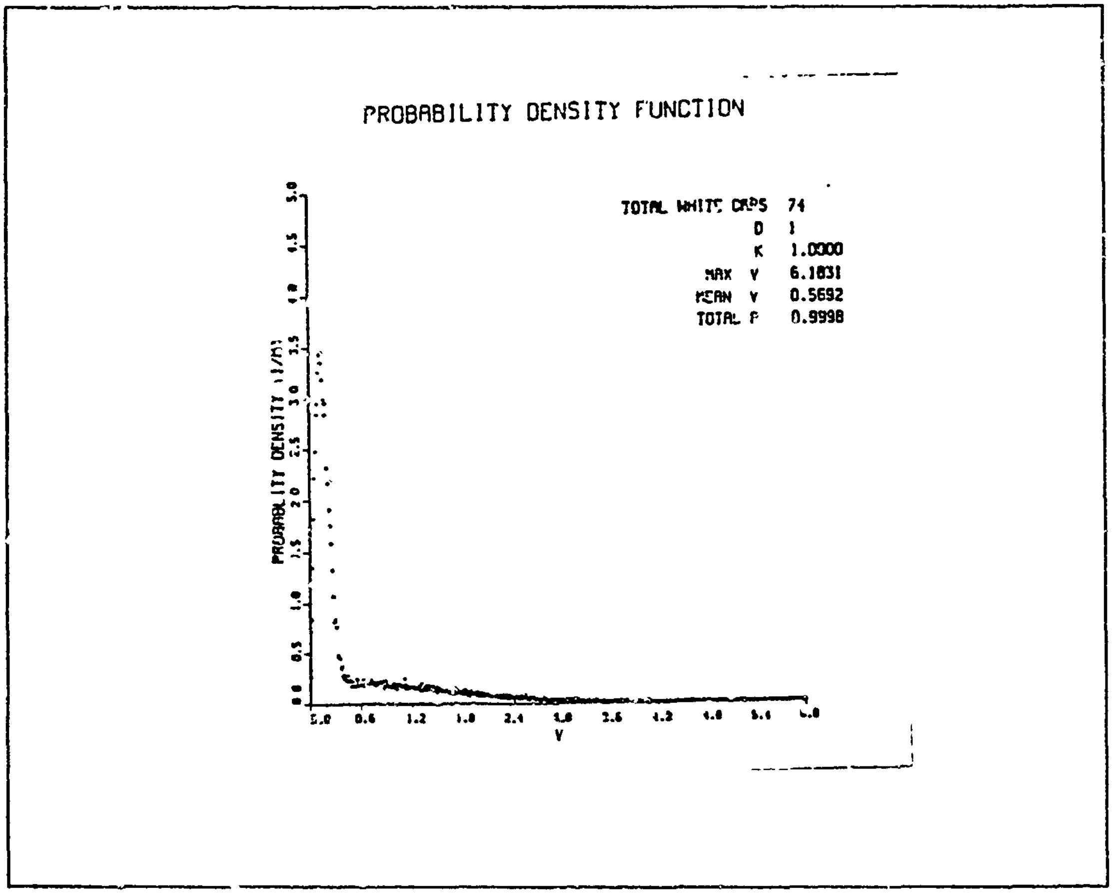

Figure 36. Simulated PDF of clutter voltage, observing time 750 seconds, total whitecaps is 74, Randomness factor = 1.

When the wind speed increases, the rate parameter of the Poisson process increases. Figure 36 is the result of 74 breaking waves occurring over the entire observation time. The mean clutter voltage is 0.5692 , while the mean clutter voltage in Figure 35 is 0.1501.

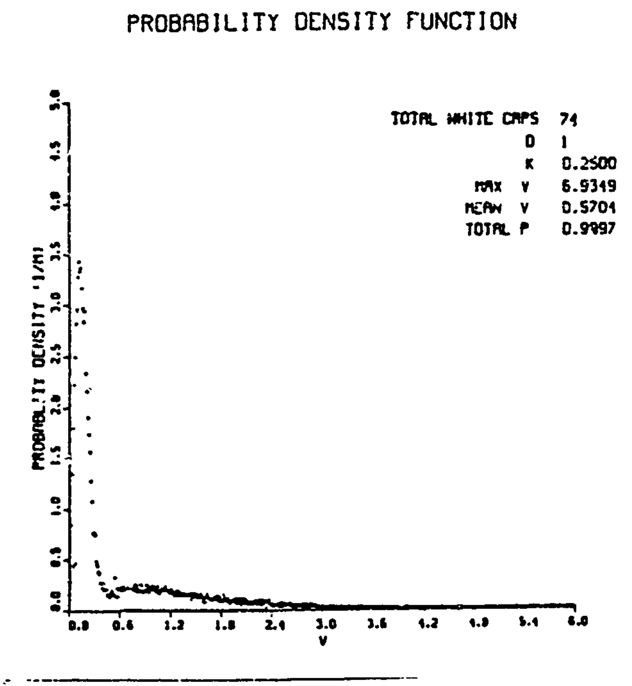

Figure 37. Simulated PDF of clutter voltage, observing time 750 seconds, total whitecaps is 74, Randomness factor = 0.25.

This increase in the mean clutter voltage is due to contributions by the breaking waves. This can be observed from the higher tail in the probability of Figure 36, compared to that of Figure 35. Notice the total probability in this simulation up to a clutter voltage of 6 is 0.9998. This means there is only a negligible number of samples greater than 6. Note that the maximum sample value included is 6.1831.

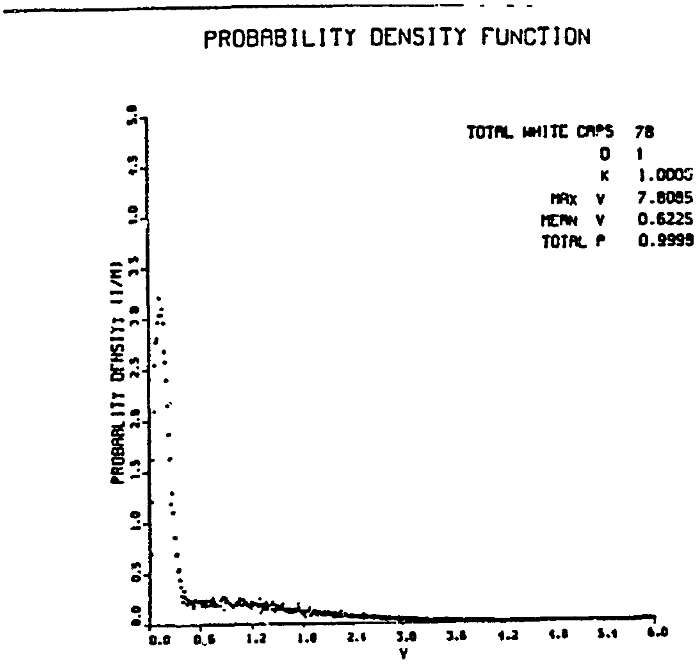

Figure 38. Simulated PDF of clutter voltage, observing time 750 seconds, total whitecaps is 78, Randomness factor = 1.

Figure 37 uses a simulation with the same seeds for random generators as those used in the simulation of Figure 36. In both cases there are 74 breaking waves occurring over the entire observation time. The only difference is that in Figure 37 the randomness factor of the whitecaps is 0.25 while the randomness factor in Figure 36 is 1. The contributions to the probability density function from the unbroken water and the whitecaps are similar. But in the conjunction part of the probability density function of Figure 37, the 0.25 roughness factor causes a sharper notch.

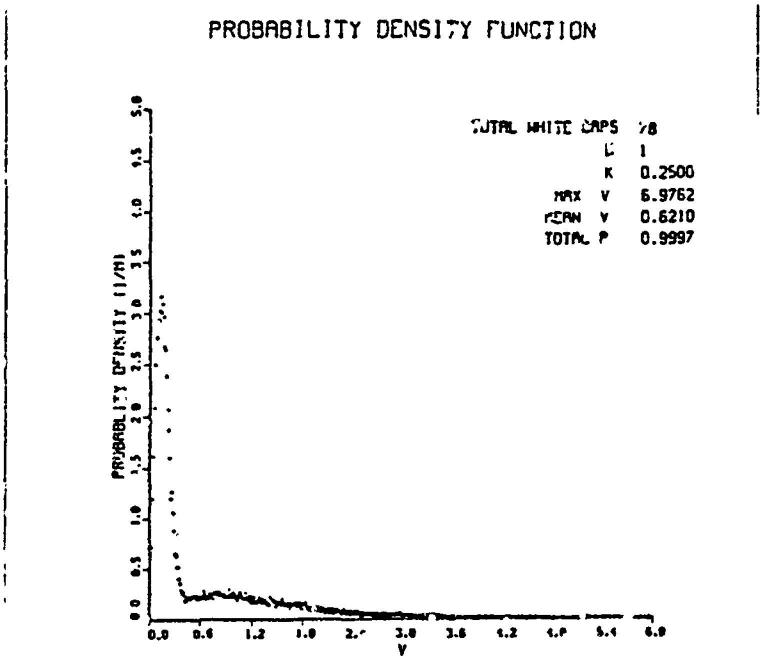

Figure 39. Simulated PDF of clutter voltage, observing time 750 seconds, total whitecaps is 78, Randomness factor = 0.25.

Figure 38 is a different run of the simulation, with 78 whitecaps occurring. The roughness factor is 1. Figure 39 uses the same seeds for random generators as those used in Figure 38, with the randomness factor of the whitecaps taken as 0.25. The difference Figure 38 and Figure 37 is similar to that between Figure 36 and Figure 37.

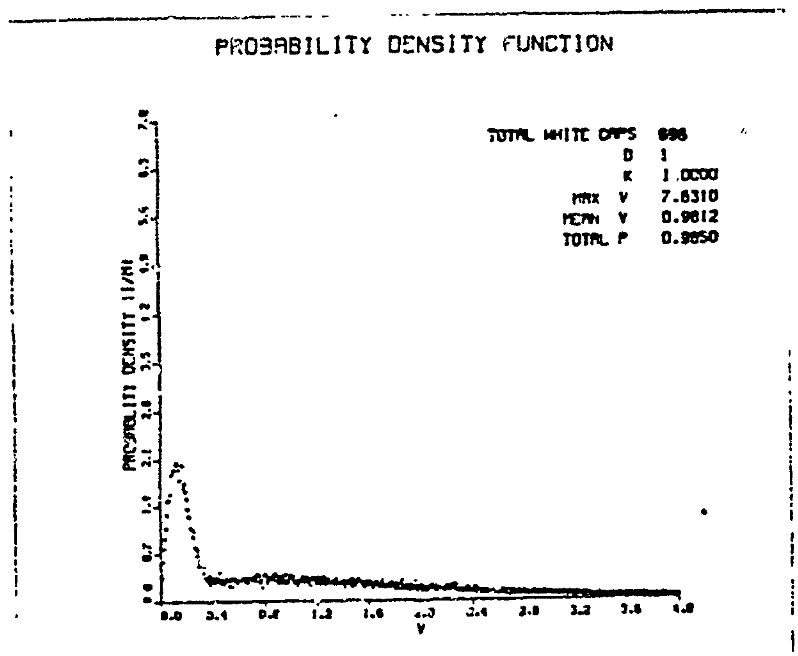

Figure 40. Simulated PDF of clutter voltage, observing time 750 seconds, total whitecaps is 696, Randomness factor = 1.

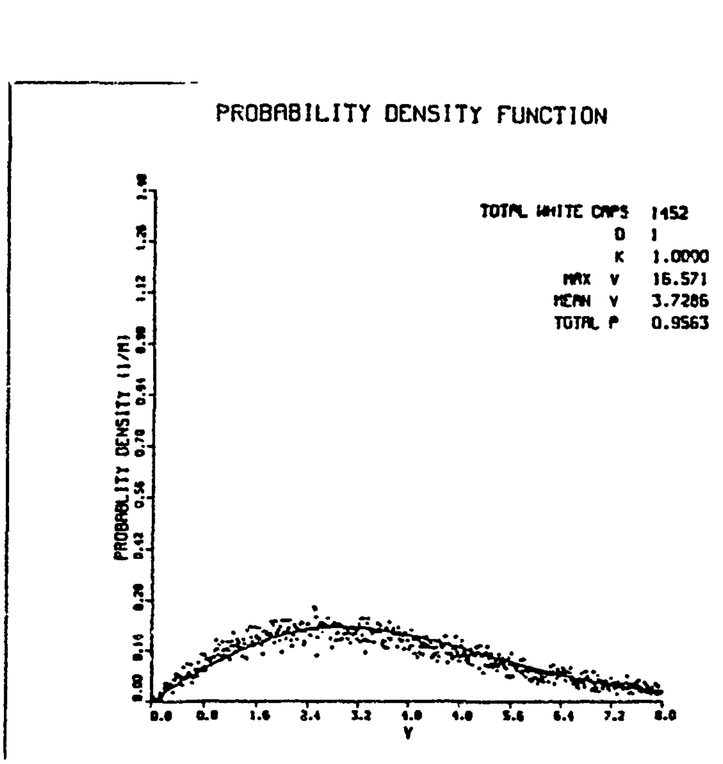

Figure 41. Simulated PDF of clutter voltage, observing time 200 seconds, total whitecaps is 1452, Randomness factor = 1. Solid line is Rayleigh distribution with the simulated sample mean.

In Figure 40, 696 whitecaps appear over the simulation period. The peak corresponding to the Rayleigh distribution of Figure 35 diminishes further because there are stronger contributions from the breaking waves. The tail of the clutter PDF in this case becomes more pronounced. The maximum clutter voltage sampled increases to 7.831 , The mean clutter voltage increases to 0.9512. The total probability up to the clutter voltage of 4 in this figure is 0.985. The peak probability density at zero clutter voltage to 2.1 .

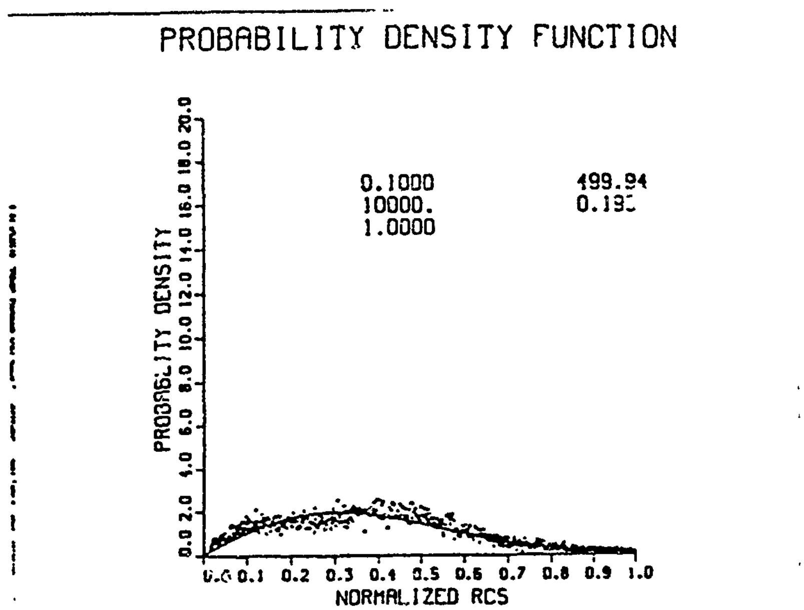

Figure 42. Simulated PDF of clutter voltage, 1000 scattering sample from whitecaps only, Randomness factor = 0.1.

Figure 41 is a run of simulation with a greater rate parameter. The Poisson process generates many more breaking waves over the entire observation period. The observation time is 200 seconds. There are 1452 whitecaps occurring. The peak of the original Rayleigh distribution of Figure 35 caused by the scattering from the unbroken water now vanishes completely. The entire probability density function is dominated by the scattering from whitecaps. It is similar to the Rayleigh distribution with a mean of 3.7286.

The solid line in Figure 41 is the Rayleigh distribution with the simulated sample average as its mean.

In Figures 36 and 38 the probability density functions show a sharper notch in the conjunction between contributions from the whitecaps and the unbroken water compared to Figure 37 and 39. The differences are due to the fact that the randomness factor of whitecaps for Figure 37 and 39 is a smaller number. The probability distribution of the scattering from growing whitecaps should be further investigated. Thus, a program is designed to collect samples from the breaking waves only.

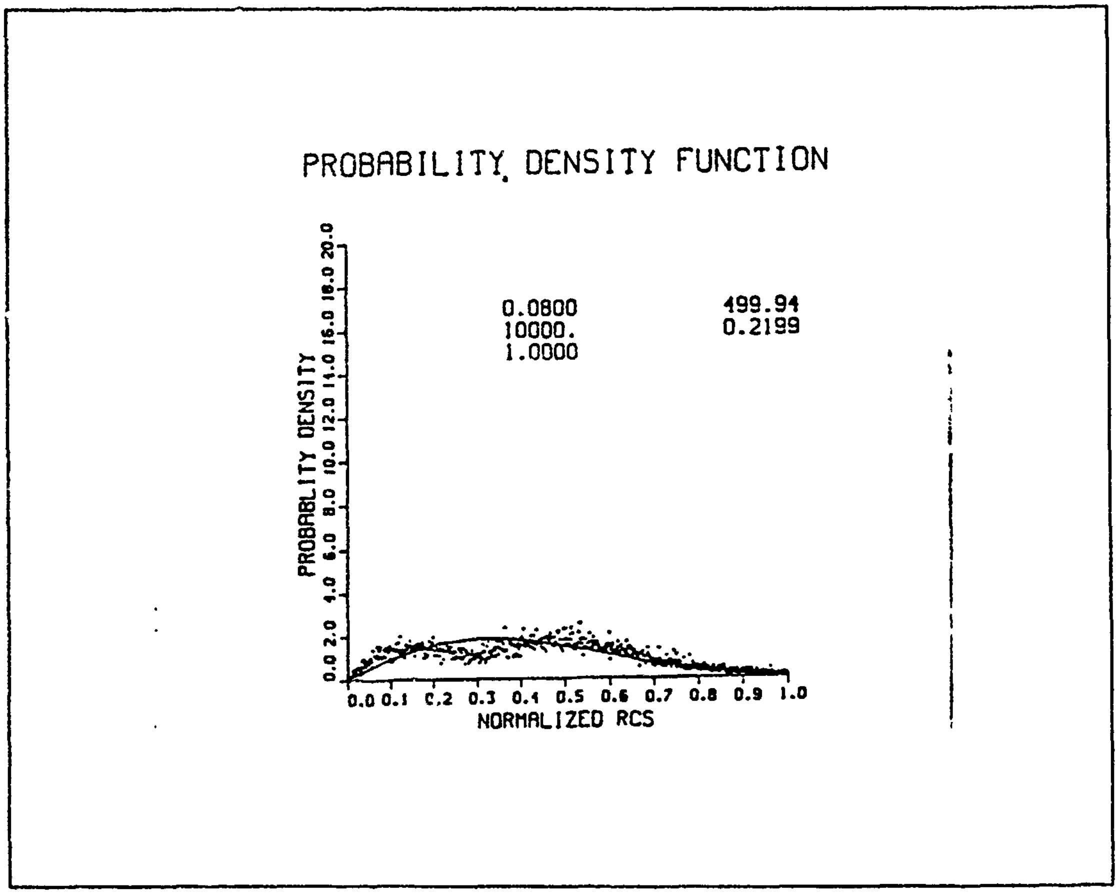

Figure 43. Simulated PDF of clutter voltage, 1000 scattering sample from whitecaps only, Randomness factor = 0.08.

Figure 39 is the probability density function of normalized clutter voltage calculated from 10,000 independent samples from whitecap. The randomness factor is 0.1. The reason for using normalized clutter voltage is that it is necessary to investigate the shape of probability density function when the randomness factor is small. In this figure, there is a ripple in the PDF. If the contribution in PDF from unbroken water overlaps the normalized clutter voltage from 0 to 0.3, then depending on the phase of the signals, the ripple at 0.3 may cause a sharp notch in the probability density function of the combined signals.

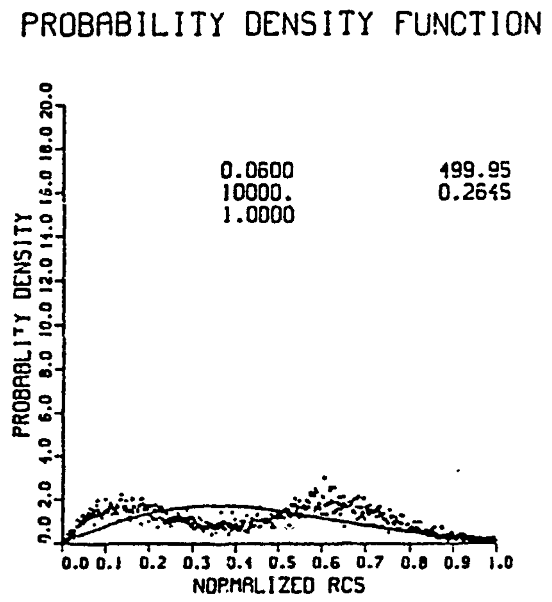

Figure 44. Simulated PDF of clutter voltage from whitecaps only, Randomness factor = 0.06.

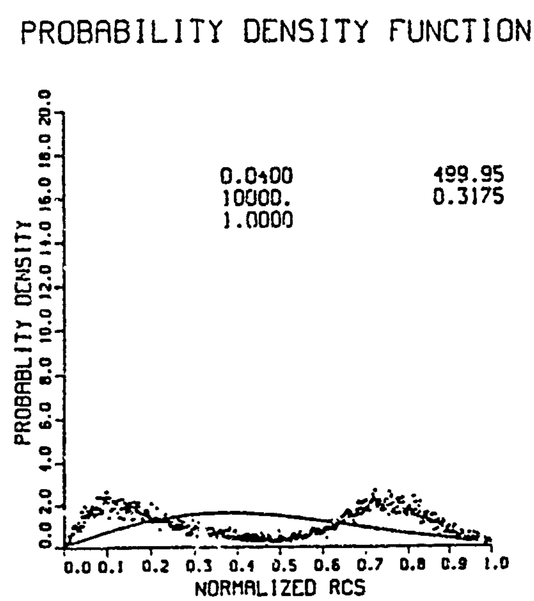

Figure 45. Simulated PDF of clutter voltage from whitecaps only, Randomness factor = 0.04.

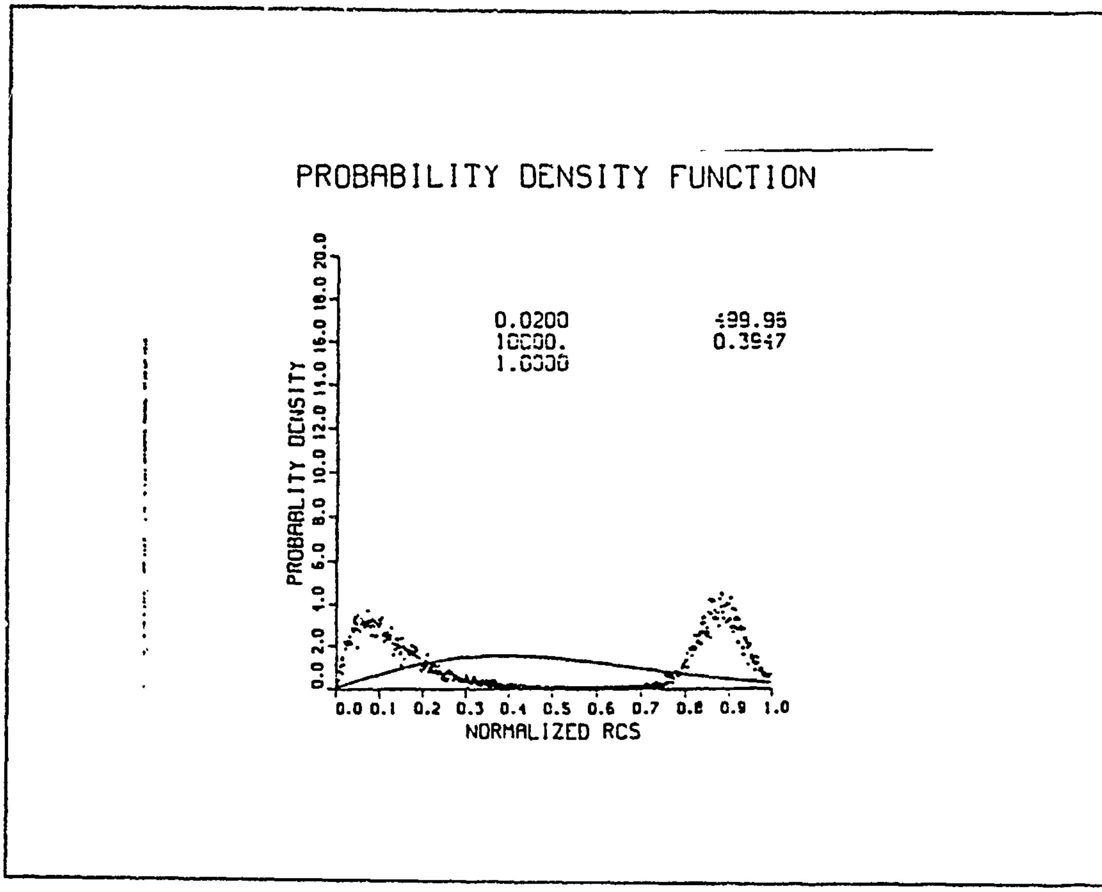

Figure 46. Simulated PDF of clutter voltage from whitecaps only, Randomness factor = 0.02.

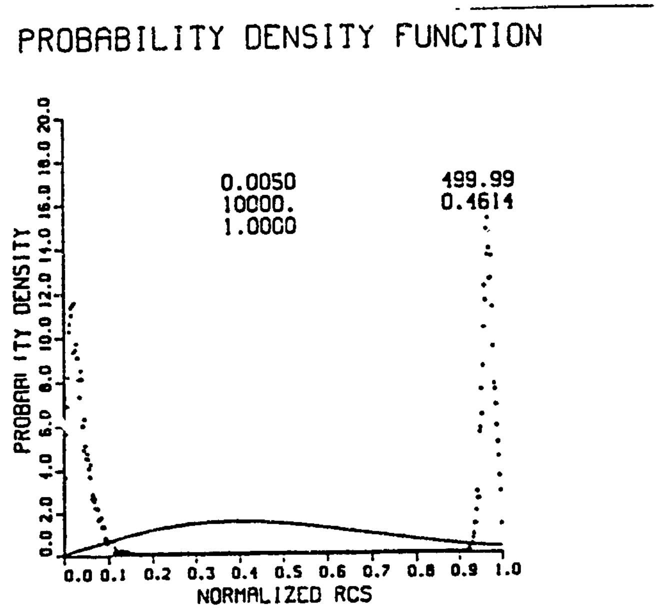

Figure 47. Simulated PDF of clutter voltage from whitecaps only, Randomness factor = 0.005.

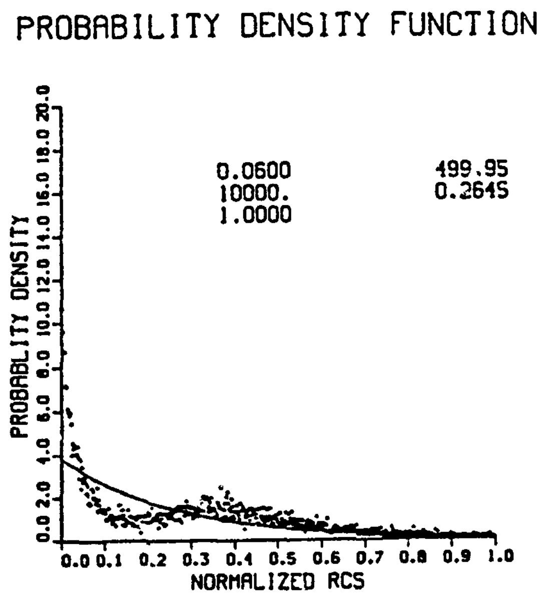

Figure 48. Simulated PDF of RCS from white caps only, k = 0.6.

Figures 42 to 47 are probability density functions of the clutter voltage scattered from growing whitecaps, with the randomness factors 0.1, 0.08, 0.06, 0.04, 0.02, and 0.005 respectively. Figure 48 is the simulated PDF of RCS with k = 0.6. Note that the PDF s have two peaks and their peaks becomes farther separated when k decreases. Meanwhile the peak values of the probability density functions increase while the randomness factor decreases. For a randomness factor of 0.005, the probability density function is zero between 0.15 and 0.9 normalized clutter voltage.

It can be concluded that the sharp notches in Figures 37 and 39 are caused by a small randomness factor.

In Figures 49 and 50, the same set of seeds of the random number generator is used for the simulation, with randomness factors of 0.1 and 0.05 respectively.

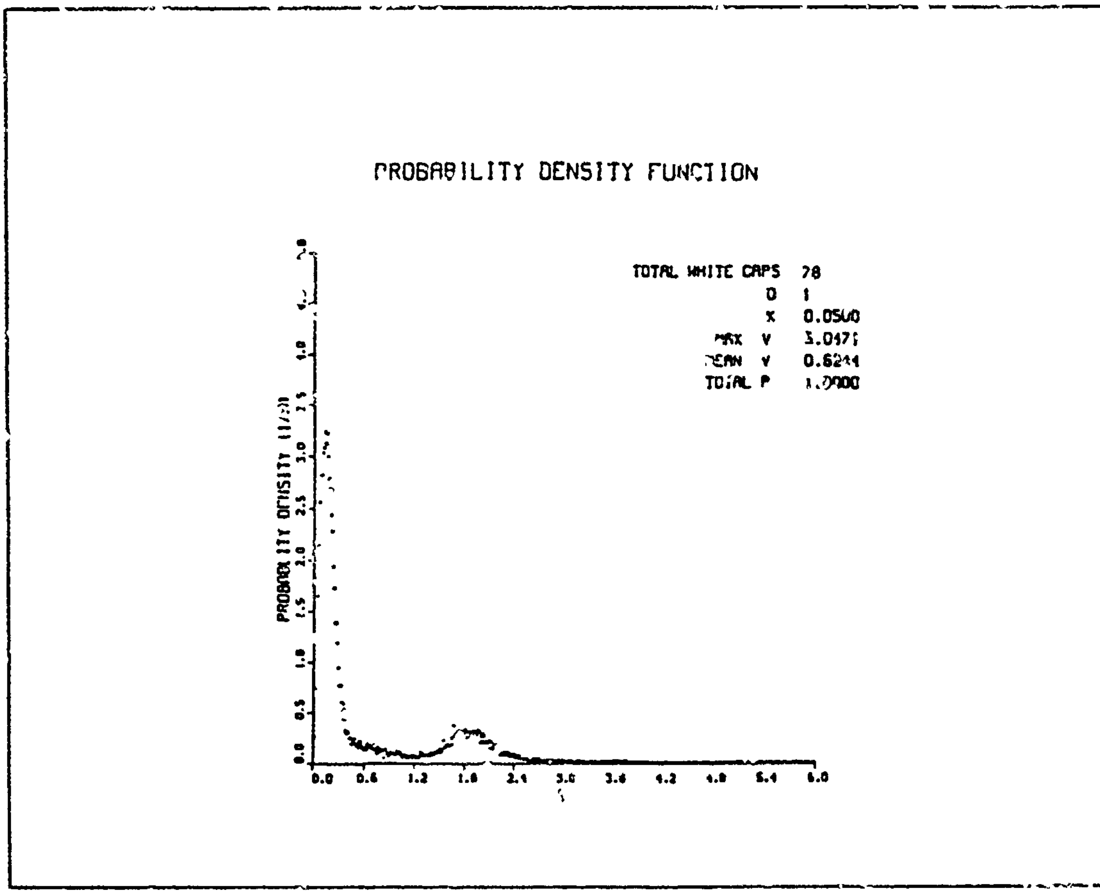

Figure 49. Simulated PDF of clutter voltage, observing time 750 seconds, total whitecaps is 78, Randomness factor = 0.05.

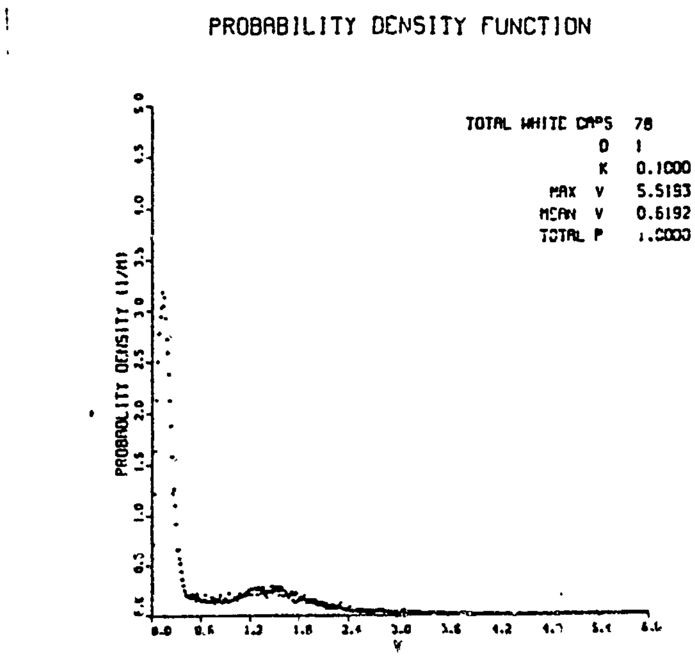

Figure 50. Simulated PDF of clutter voltage, observing time 750 seconds, total whitecaps is 78, Randomness factor = 0.1.

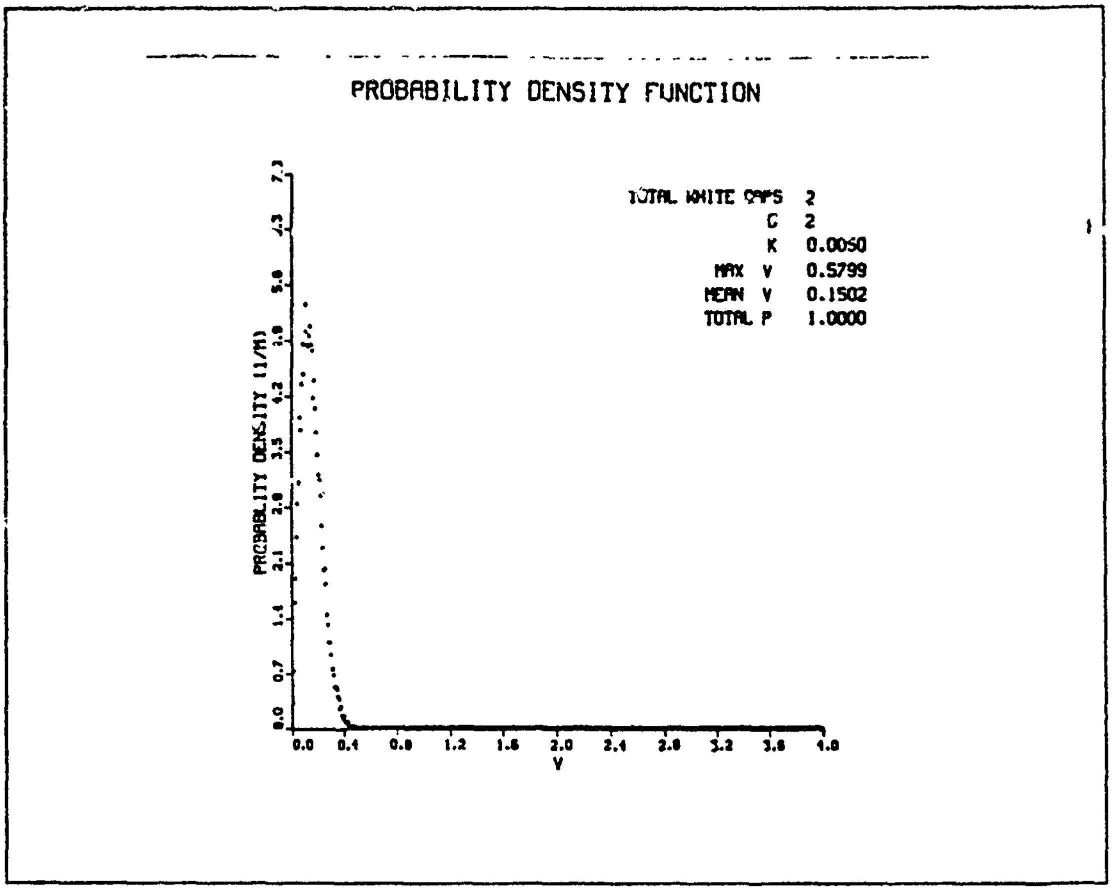

Figure 51. Simulated PDF of clutter voltage from whitecaps only, Randomness factor = 0.005, internal decorrelation time = 2.

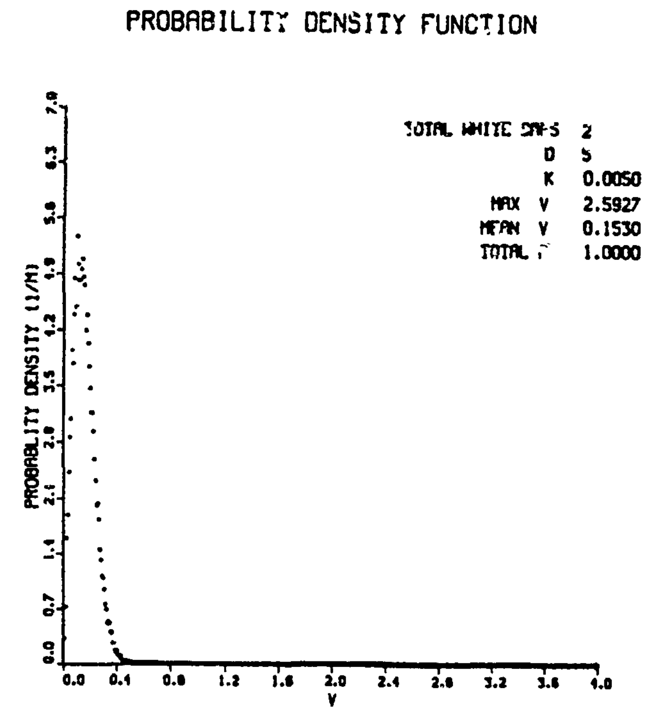

Figure 52. Simulated PDF of clutter voltage from whitecaps only, Randomness factor = 0.005, internal decorrelation time = 5.

Figure 51 shows the results of simulation with an internal decorrelation time of 2. Figure 52 is the results of simulation with an internal decorrelation time of 5, with the same seeds of random number generators. It shows little difference when the internal decorrelation time is changed by this amount.

VI. SUMMARY

Many measurements have been made to analyze the probability distribution of sea clutter. Several probability density functions have been used by other researchers to fit those measured data. To date, none of them appears satisfactory. A different approach is proposed to construct a model with a few physical parameters which describe the sea surface and then to obtain the clutter voltage in terms of simulation. Those physical parameters will be determined by fitting the simulated clutter voltage with measured data.

In this thesis, the probability density function of sea clutter voltage is investigated through simulation. The results show that the number of breaking waves, which depends on the wind speed and the randomness factor of whitecaps, determine the shape of the probability density function of the clutter voltage.

The randomness factor of the whitecaps causes a very interesting change in the shape of probability density function. No familiar PDF can fit these forms. These probability density functions all meet the necessary conditions that the breaking waves contribute to a tail in the high clutter voltage region. This explains the higher false alarm rate in detecting the presence of target return with a high resolution radar.

APPENDIX A SIMULATION PROGRAM OF BACK SCATTERING FROM WHITECAPS

define parameters and arrays

```
   REAL K
   REAL*8 SEED,S,RS(200)
   DIMENSION U(20000),X(200),Y(200),C(200),AD(200)
   INTEGER D,NOS,NZ
```

enter internal decorrelation time, seed for random generator, and whitecap randomness factor

```
   READ*, D,SEED,K
```

define whitecap size and phase constant

```
   NZ=128
   TH=1
   Z=1
   NN=2*NZ
```

call uniform random number generator to get 2 random numbers as the seeds to be used in calling random generator for each zone size.

```
   CALL GGUBS(SEED*183562.,NN,RS)
   PRINT*, NZ
```

calculate scattering signal for each zone size.

```
   DO 1 I=1,NZ
```

determine number of zones to be updated.

```
    NS=((I/D)+1)*2
```

get phase and amplitude for zones to be updated

```
    CALL GGUBS(RS(I)*1006243.,NS,U)
```

update phase and amplitude.

```
    IC=(I/D)+1
    DO 2 J=1,IC
     JJ=J-1
     II=I-JJ*D
     X(II)=U(J)
2    Y(II)=U(J+IC)
    A=0.
```

```
      C(I)=0.
c     calculate scattering signal.
      DO 3 L=1,I
        IF(Z.EQ.0) THEN
          A=(-1)**(L-1)*(1-K*X(L))*COS(TH)+A
          B=(-1)**L*(1-K*X(L))*SIN(TH)+B
        ELSE
          A=(-1)**(L-1)*(1-K*X(L))*COS(3.14159*K*(Y(L)-.5))+A
          B=(-1)**L*(1-K*X(L))*SIN(3.14159*K*(Y(L)-.5))+B
        ENDIF
3     CONTINUE
1     C(I)=A**2+B**2
      E=0.
c     find the maximum scattering sample value.
      DO 4 I=1,NZ
      AD(I)=I
      IF(C(I).GT.E) THEN
      E=C(I)
      END IF
4     CONTINUE
c     normalize all scattering signals
      DO 5 L=1,NZ
5     C(L)=C(L)/E
c     plotting statements
      CALL RESET ('ALL')
      CALL TEK618
      CALL PAGE (11.,9)
      CALL HEIGHT (.2)
      CALL AREA2D(8.,6.5)
      CALL XNAME('ZONE NUMBERS',11)
      CALL YNAME('NORMALIZED RCSS',100)
      CALL HEADIN('WHITE CAP SIMULATIONS',100,1.5,1)
      CALL GRAF(0,16,128,0, 1,1)
      CALL THKCRV (.01)
      CALL CURVE (AD,C,NZ,0)
```

```
CALL FRAME
CALL HEIGHT(.15)
CALL XGRAXS(0.,1.,9.,8.,0,0,0.,0.)
CALL YGRAXS(0.,1.,9.,8.,0,0,0.,0.)
CALL BASALF('STAND')
CALL MIXALF('STAND')
CALL REALNO(K,105,1.7,4.9)
CALL RLMESS('K = S',3,1.4,5.5)
CALL RLMESS('D = S',3,1.4,5.2)
CALL INTNO(D,2,4.6)
CALL ENDPL(0)
CALL DONEPL
STOP
END
```

APPENDIX B SIMULATION PROGRAM OF SEA SURFACE MODEL

defining parameters and arrays

```
      REAL*8 SEED,DSEED,PSEED
      DIMENSION SE(9),PO(9,130),POIT(130),NR(9),PSE(18),XP(9,130)
      DIMENSION XTEP(130),YTEP(130),IP(9,10),CAP(9,10),IDX(9)
      DIMENSION YP(9,130)
```

seed for random number generator

```
      SEED=44567
```

set up parameters to call poison random number generator

```
      TU=100
      NUB=130
```

get seeds to call poisson random number generator for nine areas

```
      CALL GGUBS(SEED*1111000.,9,SE)
```

get seeds to call uniform random number generator for locations

```
      CALL GGUBS(SEED*29811117.,18,PSE)
```

proceed breaking occurrence for nine areas

```
      DO 1 I=1,9
      DSEED=SE(I)
```

get occurring times

```
      CALL POISUB(DSEED,1.,0.,TU,NUB,POIT,N)
```

two dimensional array to contain occurrence times

```
      DO 2 J=1,N
2       PO(I,J)=POIT(J)
```

array to contain number of white caps in each area

```
1       NR(I)=N
```

loop to get positions for white caps in each area

```
      DO 5 I=1,9
      II=I+9
      KK=NR(I)
```

get x and y position separately

```
      CALL GGUBS(PSEED,KK,XTEP)
      PSEED=PSE(II)
      CALL GGUBS(PSEED,KK,YTEP)
C     change references of position for sub-area
      FT=(I-.1)
      IF=FT/3
      IH=0
      IF(I.EQ.2) THEN
      IH=1
      ENDIF
      IF(I.EQ.5) THEN
      IH=1
      ENDIF
      IF(I.EQ.8) THEN
      IH=1
      ENDIF

      IF(I.EQ.3) THEN
      IH=2
      ENDIF
      IF(I.EQ.6) THEN
      IH=2
      ENDIF
      IF(I.EQ.9) THEN
      IH=2
      ENDIF
      DO 6 J=1,KK
      XP(I,J)=XTEP(J)*5+IH*5.
6     YP(I,J)=YTEP(J)*5+IF*5.

5     CONTINUE
C     loop to sample ocean surface in one resolution cell
      DO 2000 KKK=1,50
C     sample increment 0.2 sec
      SAMPT=KKK*.2+25.
```

scan all sub-areas

```
      DO 9 I=1,9
      IIF=0
```

check all white occurrence times in each sub-area

```
      DO 10 J=1,NR(I)
```

determine existing whitecaps and sizes at sampling time

```
      DIF=SAMPT-PO(I,J)
      IF(DIF.GT.0.) THEN
      IF(DIF.LE.(0.96)) THEN
      IIF=IIF+1
```

store the size of each existing whitecap

```
      CAP(I,IIF)=DIF
      PRINT*, I,J,IIF,CAP(I,IIF)
      IP(I,IIF)=J
      ENDIF
      ENDIF
10    CONTINUE
      IDX(I)=IIF
9     CONTINUE
```

beginning of plotting

```
      CALL RESET ('ALL')
      CALL TEK618
      CALL PAGE (11.,11)
      CALL HEIGHT (.2)
      CALL AREA2D(8.,8.)
      CALL XNAME('X POSITION (M)S',14)
      CALL YNAME('Y POSITION (M)S',14)
      CALL HEADIN('WHITE CAP MODELS',100,1.5,1)
      CALL GRAF(0,5,15,0,5,15)
      DO 15 I=1,9
15    PRINT*, I,IDX(I)
```

loop to plot the sizes of existing white caps in it's location

```
      DO 11 I=1,9
      IF(IDX(I).EQ.0) GO TO 11
      DO 13 J=1,IDX(I)
```

```
      X1=XP(I,IP(I,J))/2.
      Y1=YP(I,IP(I,J))/2.
      NN=CAP(I,J)/.0075
      CALL REALNO(CAP(I,J),10' X1,Y1)
      CALL REALNO(TU,105,6,9.2)
      A=.9
      CALL REALNO(A,105,6,8.9)
13    CALL REALNO(SAMPT,105,6,8.6)
11    CONTINUE
      CALL FRAME
      CALL THKCRV (.01)
      CALL ENDPL (1)
2000  CONTINUE
      CALL DONEPL
      STOP
      END

 subroutine to call poisson random number generator
      SUBROUTINE POISUB(DSEED,RLAMAX,RLAMIN,TU,NUB,P,N)
      REAL*8 DSEED
      EXTERNAL A
      DIMENSION P(500)
      CALL GGNPP(DSEED*234567,0.,TU,NUB,A,RLAMAX,RLAMIN,0,N,P,IER)
      RETURN
      END
      FUNCTION A(TL)
      A=1
      RETURN
      END
```

APPENDIX C SIMULATION PROGRAM OF TOTAL SCATTERING SIGNAL AND PROBABILITY DENSITY FUNCTION

define arrays and parameters

```
      REAL*8 SD1,SD2,SEED
      DIMENSION SCM(20000),TH(20000),PH(1500,128),CM(1500,128)
      DIMENSION XC(150),IP(50),NSIZE(50),AD(128),YSEQ(1500)
      DIMENSION TSEQ(0:1500)
      REAL K
      INTEGER D
```

enter seeds for uniform generator and poison generator, roughness factor, and internal decorrelation time

```
      READ*, SD1,SD2,SEED,K,D
      XN2=K
```

call subroutine to get a sequence of starting times, locations of breaking waves, and 128 samples of scattering for each whitecap over the whole observing time.

```
      CALL FINAL(NT,TSEQ,YSEQ,PH,CM,XC,K,D,SEED)
```

call subroutine to get 20000 samples of scattering from unbroken water.

```
      CALL NOCAP(SD1,SD2,SCM,TH,AE,XE)
```

sum the total scattering signal from unbroken water and breaking waves at 20000 sample times.

```
      DO 1 I=1,20000
```

set sample time

```
      SAMPT=(.0075/2.)+(I-1)*D*.0075
```

set initial existing breaking wave number at this time zero

```
      IIF=0
```

find whitecaps existing at this sample time

```
      DO 501 J=1,NT
```

```
second
   DT=SAMPT-TSEQ(J)
   IF(DT.GT.0) THEN
   IF(DT.LE..96) THEN
   IIF=IIF+1
determine zone size of whitecap
   IIS=DT/.0075
   NSIZE(IIF)=IIS
store white cap sequence number
   IP(IIF)=J
   ENDIF
   ENDIF
501   CONTINUE
get real part and imaginary part of scattering signal from
unbroken water
   AX=SCM(I)*COS(TH(I))
   AY=SCM(I)*SIN(TH(I))
correct phase of scattering signal from breaking wave according to
it's distance from the outer boundary of resolution cell, then add
them to the scattering from unbroken water.
   DO 503 KK=1,IIF
   THD=(15.-YSEQ(IP(KK)))*2*2*3.14159/.03
   PH(IP(KK),NSIZE(KK))=PH(IP(KK),NSIZE(KK))+THD
   AX=AX+CM(IP(KK),NSIZE(KK))*COS(PH(IP(KK),NSIZE(KK)))
503   AY=AY+CM(IP(KK),NSIZE(KK))*SIN(PH(IP(KK),NSIZE(KK)))
get clutter voltage
   SCM(I)=SQRT(AX**2+AY**2)
calculate phase
   CALL PHASE(AX,AY,TH(I))
   TEP=XN2 1     CONTINUE
   NN1=D
   DO 201 I=1,20000
201   TH(I)=SCM(I)**2
   FID=1
calculate probability density function of sea clutter voltage
```

```
      CALL PROB(20000,SCM,NT,NN1,XN2,FID)
      XN2=TEP
      FID=0
c calculate probability density function of clutter cross section
      CALL PROB(20000,TH,NT,NN1,XN2,FID)
      CALL DONEPL
      STOP
      END

c subroutine to get breaking starting times, locations, and scattering
c in the growing process of whitecap. this is the same as program in
c chapter 3 except calculation of scattering signal
      SUBROUTINE FINAL(NT,TSEQ,YSEQ,PH,CM,XC,K,D,SEED)
      REAL K
      INTEGER D
      REAL*8 SEED,DSEED,PSEED,CSEED
      DIMENSION SE(9),PO(9,200),POIT(200),NR(9),PSE(18),XP(9,200
      DIMENSION XTEP(200),YTEP(200),IP(100),NSIZE(100),CM(1500,128)
      DIMENSION YSEQ(1500),PH(1500,128),XC(1500)
      DIMENSION YP(9,200),TSEQ(0:1500)
      TU=750
      NUB=900
      CALL GGUBS(SEED*1111000.,9,SE)
      CALL GGUBS(SEED*29811117.,18,PSE)
      DO 1 I=1,9
      DSEED=SE(I)
      CALL POISUB(DSEED,1.,0.,TU,NUB,POIT,N)
      DO 2 J=1,N
2     PO(I,J)=POIT(J)
1     NR(I)=N
      DO 5 I=1,9
      II=I+9
      KK=NR(I)
      PSEED=PSE(I)
      CALL GGUBS(PSEED,KK,XTEP)
```

```
      PSEED=PSE(II)
      CALL GGUBS(PSEED,KK,YTEP)
      FT=(I-.1)
      IF=FT/3
      IH=0
      IF(I.EQ.2) THEN
      IH=1
      ENDIF
      IF(I.EQ.5) THEN
      IH=1
      ENDIF
      IF(I.EQ.8) THEN
      IH=1
      ENDIF

      IF(I.EQ.3) THEN
      IH=2
      ENDIF
      IF(I.EQ.6) THEN
      IH=2
      ENDIF
      IF(I.EQ.9) THEN
      IH=2
      ENDIF
      DO 6 J=1,KK
      XP(I,J)=XTEP(J)*5+IH*5.
6     YP(I,J)=YTEP(J)*5+IF*5.

5     CONTINUE
sort occurring times of all nine sub-areas in ascending order
      CALL TSORT(PO,NR,TSEQ,NT,YP,YSEQ)
      DO 601 I=1,NT
set seed for random generator and call subroutine to calculate
back scattering signal from breaking wave
      CSEED=TSEQ(I)*1443567
```

```
   CALL ZONEM(D,CSEED,K.CM,PH,I)
601 CONTINUE
normalize scattering voltage from breaking by 1.224745 as the mean

   DO 605 I=1,NT
   AVER=0
   DO 606 J=1,128
606 AVER=CM(I,J)+AVER
   AVER=AVER/128.
   DO 607 K=1,128
607 CM(I,K)=CM(I,K)*1.224745/AVER
find maximum sample
   CALL MAX(CM,I,XC)
605 CONTINUE
   RETURN
   END


subroutine to use poisson random number generator to get
occurring times of breaking wave.
   SUBROUTINE POISUB(DSEED.RLAMAX,RLAMIN,TU,NUB,P,N)
   REAL*8 DSEED
   EXTERNAL A
   DIMENSION P(500)
   CALL GGNPP(DSEED*234567,0.,TU,NUB,A,RLAMAX,RLAMIN,0,N,P,IER)
   RETURN
   END
   FUNCTION A(TL)
   A=.100001
   RETURN
   END

subroutine to sort starting times of breakings from all sub-
areas in ascending order.
```

```
      SUBROUTINE TSORT(PO,NR,TSEQ,NT,YP,YSEQ)
      DIMENSION PO(9,200),NR(9),TSEQ(0:1500),D(1500),PT(1500)
      DIMENSION YT(1500),YP(9,200),YSEQ(1500)
      NT=0
      DO 1 I=1,9
1     NT=NT+NR(I)
      N=1
      DO 9 I=1,9
      DO 10 J=1,NR(I)
      YT(N)=YP(I,J)
      PT(N)=PO(I,J)
10    N=N+1
9     CONTINUE
      TSEQ(0)=0
      DO 8 L=1,NT
      DO 4 K=1,NT
      D(K)=PT(K)-TSEQ(L-1)
      IF(D(K).LE.0.) THEN
      D(K)=750
      ENDIF
4     CONTINUE
      TMIN=750
      NP=1
      DO 6 I=1,NT
      IF(D(I).LE.TMIN) THEN
      TMIN=D(I)
      NP=I
      ENDIF
6     CONTINUE
      YSEQ(L)=YT(NP)
8     TSEQ(L)=PT(NP)
      RETURN
      END
```

subroutine to calculate scattering signal from breaking wave

```
      SUBROUTINE ZONEM(D,SEED,K,CM,PH,ID)
      REAL K
      REAL*8 SEED,S,RS(200)
      DIMENSION U(20000),X(200),Y(200),CM(1500,128),PH(1500,128)
      DIMENSION AD(128)
      INTEGER D,NOS,NZ
      NZ=123
      NN=2*NZ
c get 2 seeds for each zone number
      CALL GGUBS(SEED*100000000.,NN,RS)
      DO 1 I=1,NZ
c compute number of random numbers needed for scattering signal at
c each zone number
        NS=((I/D)+1)*2
c get those random numbers
        CALL GGUBS(RS(I)*100000000.,NS,U)
c update phase and amplitude in zones according to internal decorre-
c lation time and current whitecap size.
        IC=(I/D)+1
        DO 2 J=1,IC
          JJ=J-1
          II=I-JJ*D
       IF(II.EQ.0) GO TO 7
          X(II)=U(J)
2           Y(II)=U(J+IC)
7        A=0.
        B=0.
c compute real and imaginary part of scattering from breaking wave
        DO 3 L=1,I
          A=(-1)**(L-1)*(1-K*X(L))*COS(3.14159*K*(Y(L)-.5))+A
3           B=(-1)**L*(1-K*X(L))*SIN(3.14159*K*(Y(L)-.5))+B
c compute phase
```

```
      CALL PHASE(A,B,DC)
      PH(ID,I)=DC
compute clutter voltage
1       CM(ID,I)=SQRT(A**2+B**2)
    RETURN
    END
```

subroutine to calculate phase of a complex number

```
    SUBROUTINE PHASE(A,B,DC)
    DC=ATAN(B/A)
    IF(A.LE.0) THEN
    DC=DC+3.14159
    ENDIF
    RETURN
    END
```

subroutine to find the maximum number in an array

```
    SUBROUTINE MAX(CM,I,XC)
    DIMENSION CM(1500,128),XC(1500)
    XC(I)=0.
    DO 1 II=1,128
    IF(XC(I).LE.CM(I,II)) THEN
    XC(I)=CM(I,II)
    ENDIF
1   CONTINUE
    RETURN
    END
```

subroutine to calculate scattering from unbroken water

```
    SUBROUTINE NOCAP(SD1,SD2,SCM,TH,AE,XE)
```

```
      REAL*8 SD1 SD2,PSEED
      DIMENSION SCM(20000),TH(20000)
c call Gaussian random generator to get random numbers for I and Q
c channel to get Rayleigh clutter voltage
      CALL GGNPM(SD1*10023,20000,SCM)
      CALL GGNPM(SD2*10255,20000,TH)
      XE=0.
      AE=0.
      DO 1 I=1,20000
      TCM=SCM(I)
      TTH=TH(I)
      SCM(I)=SQRT(TCM**2+TTH**2)
      PSEED=I
      AE=AE+SCM(I)
      IF(XE.LE.SCM(I)) THEN
      XE=SCM(I)
      ENDIF
1     CONTINUE
c call uniform generator to get random phase between plus minus π
      CALL GGUBS(PSEED,20000,TH)
      AE=AE/20000
      DO 12 I=1,20000
      TH(I)=TH(I)*2*3.14159
12    SCM(I)=SCM(I)*.15/AE
c scale the clutter voltage by 0.15m as the mean for unbroken water.
      XE=XE*.15/AE
      AE=.15
      RETURN
      END

c subroutine to calculate average in an array

      SUBROUTINE AVERA(AV,CC,II,NJ)
```

```
      DIMENSION CC(1500,128)
      C=0.
      DO 1 I=1,NJ
1      C=C+CC(II,I)
      AV=C/NJ*1.
      RETURN
      END
```

subroutine to calculate the probability density function from 20000 independent scattering samples

```
      SUBROUTINE PROB(SZ,SAMPLE,NT,NN1,XN2,FID)
      REAL K
      INTEGER SZ,D
      DIMENSION SAMPLE(20000),P(500),HX(500)
      REAL RA(500),RA1(500),RA2(500)
      XS=0.
      DO 100 I=1,SZ
        IF(XS.LE.SAMPLE(I)) THEN
          XS=SAMPLE(I)
        ENDIF
100   CONTINUE
      XM=0.
```

fire the mean of samples

```
      DO 101 I=1,SZ
101   XM=XM+SAMPLE(I)
      XM=XM/SZ
```

set initial probability to be zero

```
      DO 105 I=1,500
105   P(I)=0.
```

set the interval of clutter voltage to count number of samples located in them.

```
      IF(FID.EQ.0) THEN
      XD=.016
      ENDIF
```

```
      JK=0
      DO 102 I=1,SZ
C determine which interval does the sample locate.
       SAP=SAMPLE(I)/XD
       ISAP=SAP
       III=ISAP+1
      IF(III.GT.500) GO TO 102
      JK=JK+1
      P(III)=P(III)+1
102   CONTINUE
      RSZ=SZ
C set initial value of total probability to be 0.
      TP=0.
C set parameter for Rayleigh distribution according to sample mean
      AAR=XM/(SQRT(3.14159/2.))
C set initial value of total probability of Rayleigh distribution
C to be zero.
      TP1=0.
C compute probability density and total probability
      DO 103 I=1,500
      HX(I)=I*XD-.5*XD
      P(I)=P(I)/(RSZ*XD)
      RA(I)=(HX(I)/AAR**2)*EXP(-1*HX(I)**2/(2*AAR**2))
      TP1=TP1+RA(I)*XD
103   TP=TP+P(I)*XD
      PRC=JK/RSZ
      PRINT*, 'TP',TP,'PERCENT',PRC
C statements to plot the probability density function
      CALL RESET ('ALL')
      CALL TEK618
      CALL PAGE (10.5,9.5)
      CALL HEIGHT (.15)
      CALL AREA2D(7.,7.)
      IF(FID.EQ.0) THEN
      CALL XNAME('RCSS',3)
```

```
CALL YNAME('PROBABLITY DENSITY (1/M**2) S',28)
ELSE
CALL XNAME(' V S',3)
CALL YNAME('PROBABLITY DENSITY (1/M)S',24)
ENDIF
CALL HEADIN('PROBABILITY DENSITY FUNCTIONS',28,1.5,1)
 IF(FID.EQ.0) THEN
 CALL GRAF(0,.6,6,0,3.6,36)

ELSE
 CALL GRAF(0,.8,8,0,.24,2.4)
 ENDIF
CALL THKCRV (.01)
CALL MARKER(15)
CALL SCLPIC(.18)
CALL CURVE (HX,P,500,-1)
CALL HEIGHT(.15)
CALL XGRAXS(0.,1.,9.,8.,0,0,0.,0.)
CALL YGRAXS(0.,1.,9.,8.,0,0,0.,0.)
CALL BASALF('STAND')
CALL MIXALF('STAND')
IF(FID.EQ.0) THEN
CALL RLMESS('MAX RCSS',7,6.3,6.43)
PRINT*, XS,'Q'
CALL REALNO(XS,105,6.7,5.73)
CALL RLMESS('MEAN RCSS',8,6.15,6.1)
CALL REALNO(XM,105,6.7,5.43)
ELSE
CALL RLMESS('MAX  V S',7,6.3,6.43)
CALL REALNO(XS,105,6.7,5.73)
CALL RLMESS('MEAN  V S',8,6.15,6.1)
CALL REALNO(XM,105,6.7,5.43)
ENDIF
CALL RLMESS('TOTAL P S',8,6.15,5.77)
CALL REALNO(TP,105,6.7,5.13)
```

```
CALL RLMESS('TOTAL WHITE CAPSS',16,5,7.5)
CALL INTNO(NT,6.8,6.65)
CALL RLMESS('DS',1,7.1,7.15)
CALL INTNO(NN1,6.8,6.35)
CALL RLMESS('KS',1,7.1,6.8)
CALL REALNO(XN2,105,6.7,6.05)
PRINT*, TP1
CALL ENDPL (0)
RETURN
END
```

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